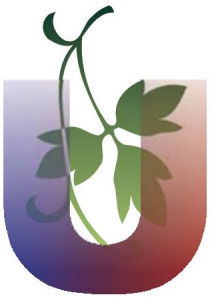
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V.H. Binghi

MAGNETOBIOLOGY
EXPERIMENTS AND MODELS

SECOND EDITION



MOSCOW 2002

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V. N. Binghi

Magnetobiology: experiments and models. Moscow, MILTA, 2002. – 592 p.

The World Health Organization considers the increase in electromagnetic pollution in workplaces and residential areas as a factor
stress for the human body. Power lines, household appliances, mobile phones... People are immersed in natural and man-made electromagnetic fields. They are not indifferent to these fields, just like
and other living systems. This fact is confirmed by a huge number of scientific papers. However, most authors note the presence of a problem: the physical cause of the phenomenon is still unknown and paradoxical. What processes
What underlies the interaction of electromagnetic fields with biological systems? This book examines this issue from a physics perspective.
There are no competing publications.

The book was written between 1996 and 2000 and is based on the author's 20 years of research in the field of electro- and magnetobiology. Most of the results have been published in various peer-reviewed scientific journals. The book presents a thorough analysis of virtually all currently known experimental data in magnetobiology that carry physical information. Existing theoretical models of the phenomenon are examined, and the mechanism of quantum interference, which explains a significant part, is outlined.
experimental data.

The author, Vladimir Nikolaevich Bingi, is a graduate of MIPT and received a degree PhD in Physics and Mathematics at the Lebedev Physical Institute in 1982. Published about 50 articles in specialized scientific journals. Currently
Head of the Radiobiology Laboratory at the General Physics Institute of the Russian Academy of Sciences and is a member of the Russian National Committee for Non-Ionizing Radiation Protection radiation.

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Preface

The book is intended primarily for physicists, but will also be useful to specialists in the fields of chemistry, biology, medicine and related fields.
directions. The author of the book, V. N. Binghi, is a well-known specialist in the field of magnetobiology, a member of the American Society
Bioelectromagnetics (BEMS).

The field of electromagnetobiology is developing very rapidly. Monographs are appearing devoted to the practical and ecological aspects of this science. At the same time, the fact of the biological action of weak magnetic fields remains paradoxical from a physical point of view. This book examines precisely this problem, compensating for the lack of theoretical approaches. It selects and summarizes experiments that provide information on the primary physical processes of magnetoreception, frequency and amplitude spectra under the influence of weak magnetic fields.
magnetic fields. An analysis of known hypotheses about the mechanisms is presented such an impact. The method of physical assessments used in the book allows one to quickly determine the prospects of a particular idea in
magnetobiology. A general basis for explaining the biological effects of magnetic fields is proposed. The interference of quantum states of ions and molecules is the subject of the author's original hypothesis.

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explains the paradoxes of the non-thermal action of electromagnetic fields. The theory of interference of quantum states of ions is based on "first" physical principles and is successfully combined with experiment. Essentially, this is a reasonable formulation of the problem of interaction of electromagnetic fields with biological systems. The theory of V. N. Binga leaves room for further research, which will undoubtedly attract young specialists to this field of science. This book can be recommended for them as an introductory course.

The subject of the book could probably be called magnetobiological spectroscopy. The latter is unique in that information about physical processes in biophysical structures is extracted not only by physical but also by biological means. Apparently, we can also talk about the emergence of a new direction—magnetobiological—in theoretical biophysics. This direction

continues to generate much debate, but research
In this area it is necessary to continue, observing all the rigor of modern mathematical and physical approaches.

Academician of the Russian Academy of Sciences

Nobel Prize laureate
A. M. Prokhorov



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From the author

The first edition of the book1 was published in English with a preface.
the late Academician Prokhorov. The author is indebted to Alexander Mikhailovich
for his kind attitude and valuable comments on the content.
books.

The author is grateful to E.E. Fesenko. His interest in the work, support of original research, and discussion of the results influenced
the composition of the book, the interaction of its parts. The author is sincerely grateful V.A. Milyaev for useful discussions and organization of interaction with
by the team of the General Physics Institute of the Russian Academy of Sciences.

Reviews and feedback on the book were provided by V.B. Akopyan, G. Berg, F. Bersani, K. Blackman, R. Goldman, Yu.G. Grigoriev, B. Greenbaum, S.D. Zakharov, A. Libov, V.I. Lobyshev, V.P. Makarov, R. Fitzsimmons, A.V. Zolotaruk; the author is grateful to them for this assistance.

Meetings and discussions with colleagues and friends have always been a fruitful source of new ideas. In this regard, it is useful
The author was influenced by A.E. Akimov, I.Ya. Belyaev, O.V. Betsky, L.A. Blumenfeld, Yu.I. Gurfinkel, A.P. Dubrov, A.N. Kozlov, A.A. Konradov, V.K. Konyukhov, V.V. Lednev, M. Fillon-Robin, A.V. Savin, E.V. Stepanov, I.M. Shvedov, S.E. Shnol.

A.P. Repyev and M.G. Edelev translated the book into English. The author is grateful to them for their cooperation. The author is grateful to A.Ya. Grabovshchiner for consultations on electromagnetic issues.
therapy and assistance in publishing the book in Russian.

The constant support of parents, relatives, and loved ones is invaluable. The author is especially grateful to
E.O. Turantaeva. Without her patient participation, constant attention,
Without your help and care, writing this book would have been impossible.

In this edition, the section devoted to molecular gyroscopes has been revised, corrections and additions have been made.

1V.N. Binhi. Magnetobiology: Underlying Physical Problems. Academic Press, San Diego, 2002.

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Designations of physical quantities

me, mp	mass of an electron and a proton
M, q	mass and electric charge of a particle
S, ÿ	part, in units , and the magnetic moment of the spin tsy
ÿ = ÿ/S	gyromagnetic ratio
I	moment of inertia
ÿ	magnetic susceptibility
A,A0	electromagnetic field potentials (EMF)
H, B	magnetic field tension and induction
E, D	EP tension and displacement
HDC, HAC	tension of constant and alternating current MP
h = HAC/HDC ÿ ÿc =	relative amplitude of MP circular frequency of the external field
qHDC/Mc f =ÿ/ÿc ÿN = ÿHDC ÿR =	cyclotron frequency relative frequency of MP
ÿHAC ÿ= ÿM c/ q ÿ0 =ÿc/2 ÿ1 = qHAC/2Mc	NMR frequency Rabi frequency ion-isotope constant
	Larmor frequency Larmor frequency by the amplitude of the alternating current MP
L, H	Lagrange and Hamilton functions
H	Hamiltonian
P , P, p, L, L,I	vector and scalar momentum operators and angular momentum and their eigenvalues
S = ÿ/2, S	vector and scalar spin operators
I , I	the same for nuclear spin
M = ÿS /S ÿ	magnetic moment operator
=(ÿ1,ÿ2,ÿ3) ÿ ÿi,ÿi	Pauli matrices
	wave function eigenfunctions of the Hamiltonian and their energy
m	magnetic quantum number
T	absolute temperature

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Mathematical notations

ab is the scalar product of vectors a × b is the vector product
·· — quantum mechanical averaging {,} — commutator of operators M[..] — mathematical expectation ÿ — equal in order of magnitude
, — real and imaginary parts ÿ — delta function

Fundamental constants

e = 4.803 x 10ÿ10 CGS units — electron charge = 1.055 x 10ÿ27 erg s — Planck constant c = 2.998 x 1010 cm sÿ1 — speed of light in vacuum me = 9.109 x 10ÿ28 g — electron mass mp = 1.673 x 10ÿ24 g — proton mass ÿB = e/2mec = 9.274 x 10ÿ21 erg Gÿ1 — Bohr magneton ÿN = e/2mpc = 5.051 x 10ÿ24 erg Gÿ1 — nuclear magneton ÿp = 2.7928 ÿN — proton magnetic moment ÿ = 1.3807 x 10ÿ16 erg Kÿ1 — Boltzmann constant NA = 6.022 1023 molÿ1 — Avogadro's number

Some physical quantities

ÿTÿ 4.14 10ÿ14 erg — coefficient of thermal energy per degree of freedom at T = 300K 1 amu = 1.661 10ÿ24 g — atomic mass unit 1 A/m = 1.26 10ÿ2 Oe — units of magnetic field strength 1 V/m = 0.333 10ÿ4 CGS units of electric field strength = 3.336 10ÿ30 C m = 10ÿ18 CGS units of electric dipole-1D = e 1 Å A moment
1 Ohm = 1.11 x 10ÿ12 CGS units of electrical resistance 1 mW/cm2 = 104 erg/(cm2s) — units of energy flux density 1 cmÿ1 = 30 GHz — unit of frequency (f /c = ÿÿ1) 1 eV = 1.602 x 10ÿ12 erg

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List of abbreviations

a.m.u.	atomic mass unit
AC–DC	English, variable-constant
GMP	geomagnetic field
IR	infrared
EHF	extremely high frequency
ELF	extremely low frequency
MBE	magnetobiological effect
MM	millimeter
MP	magnetic field
rel. units	relative units

ex. units arbitrary units
RF radio frequency
RP radical pair
microwave ultra-high frequency
SQUID superconducting quantum interferometer
SR stochastic resonance
UHF ultra-high frequency
UV ultraviolet
CRT cathode ray tube
EM electromagnetic
EMF electromagnetic field
EP electric field
EPR electron paramagnetic resonance
NMR nuclear magnetic resonance

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Chapter 1

Introduction

Magnetobiology is a new synthetic field
knowledge, the facets of which are shaped by a wide variety of sciences, from physics to medicine. Its core lies in the field of biophysics. Magnetobiology has achieved significant development only in the last 10–20 years.
years. At the same time, magnetobiology is a problem that has been
For a relatively long period of time, magnetobiology has not received a satisfactory explanation. There is no theory or general physical concepts of magnetobiology. There are practically no predictive theoretical models. The problem is related to the paradoxical nature of biological
the action of weak low-frequency magnetic fields, which in energy
are far from comparable with the characteristic energy of biochemical transformations. Because of this, the very existence of the problem raises doubts among a significant part of the scientific community - despite the enormous number experimental evidence.

Long-term observations indicate that some electromagnetic fields pose a potential health hazard.
people and are no less significant a factor than temperature,
pressure and humidity [87]. As awareness of this fact grows, the task of studying the mechanisms of biological action of electromagnetic
fields is becoming increasingly relevant.

Specialized biological magnetoreceptors, in addition to
biomagnetite particles in some bacteria do not exist in nature,
Therefore, it is important to understand how the magnetic field signal is transformed into a response of the biological system. In the low-frequency range
the magnetic field penetrates living matter with virtually no interference

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tissue. It acts on all particles of the tissue, but not all of the particles are involved in the process of transmitting information about the magnetic field to the biological level. The primary processes of interaction of a magnetic field with particles of matter, electrons, atoms, molecules, are purely physical processes. Charged particles of living matter, ions participating in biophysical and biochemical processes, magnetic moments of atoms and molecules, are, apparently, mediators in the transfer

magnetic field signals to the next biochemical level. Fine regulation of protein activity, carried out by biophysical mechanisms involving magnetosensitive intermediates, leads

to a shift in metabolic processes. Starting from this level, the effect of the magnetic field can be observed by changing the concentrations of metabolic products.

Biological effects of magnetic fields are often observed through the vital parameters and behavior of individuals and populations. Experiments typically involve observing the relationship between the characteristics of a physical agent—the external magnetic field.

and the biological effects it causes. Intermediate levels organizations of the living system: biophysical, biochemical and physiological, are beyond the scope of the experiment, but at the same time strongly influence its results. Between cause and effect, a "black box" with uncontrollable properties appears, which prevents the clarification of cause-and-effect relationships. At the same time,

It is practically impossible to trace the effect of weak magnetic fields at the level of individual biochemical reactions or biophysical structures using physical and chemical methods. Known magnetochemical effects are realized in relatively strong magnetic fields, and their possible involvement in magnetoreception remains

is in doubt [92]. Thus, magnetobiology has objective difficulties associated with the fact that it necessarily combines questions of physics, biophysics, biochemistry and biology.

In addition to an analytical review of research in magnetobiology, this book presents the first detailed description of the interference effect of quantum ionic states within protein cavities. Based on the Schrödinger and Pauli equations, the quantum dynamics of ions is considered under idealized conditions in parallel magnetic fields, as well as in a number of other combinations of magnetic and electric fields. The ion's nuclear spin and the nonlinear reaction of the protein are taken into account.

on the redistribution of the probability density of the ion. Formulas were obtained for the magnetic field-dependent part of the dissociation probability of the

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ion-protein plex. The basic formula that allows you to calculate
the magnitude of the possible magnetobiological effect in parallel
constant HDC and alternating HAC magnetic fields, has the form1

$$P = \sum_{m=m;n} |amm|^2 \frac{\sin 2A}{A2} J_n^2 \left(\frac{m}{2}\frac{h}{f}\right), A = \frac{1}{2}(m + nf\ddot{y}).$$

Here m is the magnetic quantum number, m = m ÿ m , ÿ= T ÿc —
a dimensionless parameter that depends on the properties of the ion-protein complex,
ÿc = qHDC/M c is the ion cyclotron frequency, T is the reaction time
protein to change the state of the ion, f = ÿ/ÿc and h = HAC/HDC —
dimensionless frequency and amplitude of the variable component of the magnetic
fields, Jn is the Bessel function of order n. The elements amm are constant
coefficients that determine the initial conditions of the ion's stay in the protein
cavity. The characteristic frequency and amplitude interference spectra in various
magnetic fields were calculated, including
number in pulsed fields, in conditions of "magnetic vacuum", taking into account
proper rotations of macromolecules, etc. They show high
level of agreement with known experimental data.

The interference of quantum states of molecules rotating inside protein
cavities, molecular gyroscopes, is considered.
properties form a consistent basis for explaining the physical mechanism of non-
thermal resonance-like biological
the action of electromagnetic fields and the solution of the so-called “kT problem”
[305].

1.1 General view on the problems of magnetobio-logy

Magnetobiology, in contrast to biomagnetism, which studies magnetic fields (MF)
of biological systems [37, 204, 313],2 is focused on the study of biological reactions
and mechanisms of action
predominantly weak, less than 1 mT, magnetic fields. Interest

1This book provides formulas for calculating probable biologically effective modes of EM exposure. Their practical application may be associated with unpredictable health risks. For risk assessment, see the relevant documents on
EM safety standards, for example, [110, 479].

2Here and further, if several sources are cited, the references are given in chronological order. in a logical order.

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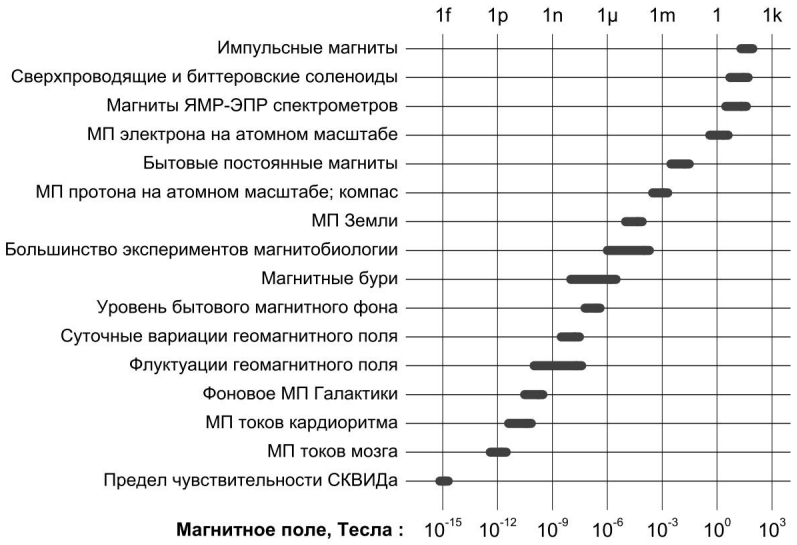


Fig. 1.1: Magnetic field levels of various natural and artificial sources; approximate boundaries are shown.

The problem of the biological effects of weak magnetic and electromagnetic fields is currently rapidly growing. The American periodical "Microwave News" provides a directory of several hundred Internet hyperlinks to organizations directly related to research in the field of electromagnetobiology.

//.

Electromagnetobiology is part of the general problem of the biological effectiveness of weak and ultra-weak physicochemical factors. It is believed that the action of such factors lies below the threshold of activation of protective biological mechanisms and, therefore, can accumulate at the subcellular level, at the level of genetic processes.

A significant increase in scientific research in electromagnetic biology initiated by the development and creation of the school of Academician Devyatkov in the USSR in the 1960s, millimeter-wave EM generators.

Almost immediately it was discovered that such microwaves cause biological effects [75]. These studies were reproduced abroad. What was interesting was that the radiation power was often too low to cause any significant heating.

tissues. At the same time, the quantum of radiation energy is two orders of magnitude smaller

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characteristic energy of chemical transformations ÿT . In addition, the effects were observed only at some, but not all, frequencies, which also indicated the non-thermal nature of the effects. The effects of microwaves also depended on the frequency of their low-frequency modulation. Therefore, already in In the 1980s, the biological effects of low-frequency magnetic fields in the range of about 10–100 Hz were reliably recorded. These facts are important because this range covers the frequencies of industrial and household electrical appliances.

Interest in magnetobiology is driven primarily by environmental factors. Human interference in natural processes has reached dangerous levels. The environment is polluted by industrial and household waste. Electromagnetic pollution is also rapidly increasing. Furthermore, there is currently no clear understanding

physicochemical mechanisms of biological action of ultraweak natural and artificial agents. We should talk about the presence of a paradox. That is, these phenomena not only cannot be explained, they seem to contradict the modern scientific picture of the world. At the same time Over time, a huge amount of factual and experimental data has been accumulated data, which indicates the reality of the phenomenon. Thus, the biological action of ultra-weak agents is a fundamental scientific a problem with a highly practical nature.

What factors are considered ultra-weak? The intuitive boundary is determined by common sense. If the effect, or more precisely, the correlation observed when exposed to some small signal, contradicts accepted views, that is, a situation of the type "This can't be!" occurs, then this signal can be classified as ultra-weak.

factors. For electromagnetic fields (EMF) of the low-frequency range, this is the background level that occurs during the operation of industrial and even household electrical appliances [66]. The diagram in Fig. 1.13 illustrates the relative level of magnetic fields, characterizing their sources and areas of application. Fig. 1.2 contains information on the spectral composition of low-frequency magnetic fields of natural origin. The spectrum, especially its part below 1 kHz, is highly dependent on the measurement location, weather, season, etc., so it is of only

conventional meaning. Urban magnetic noise in the same part, with the exception of discrete 50 Hz components and harmonics, is one to two orders of magnitude above the natural background.

Previously, it was believed that weak low-frequency magnetic fields and non-thermal electromagnetic fields are safe for humans, and the biological effect is

3The numbering of figures includes the chapter number and the number of the figure in the chapter.

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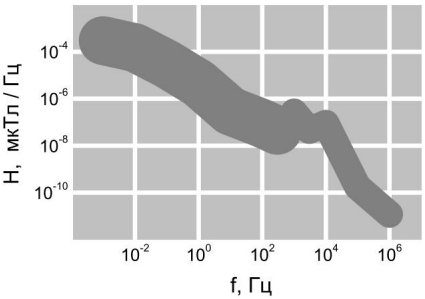


Fig. 1.2: Spectral density of low-frequency magnetic field fluctuations hundreds of natural springs, adapted from [40].

fields seemed impossible from a physical point of view. Over time, experimental data has accumulated showing the potential the danger of these fields and radiation [611, 584], the often hidden nature of their action. The consequences may appear after months or even years. The ecological significance of electromagnetic fields is becoming subject of special study. Sanitary and hygienic regulation, forecasting, control and protection from electromagnetic smog are important aspects of electromagnetic ecology. Electromagnetic safety standards are developed by various national and international organizations: the European Committee for Electrotechnical Standardization (CENELEC - Comité Européen de Normalisation Electrotechnique), German Institute for Standardization (DIN — Deutsche Institut fur Normung), National American American National Standards Institute (ANSI) International Committee on Non-Ionizing Radiation of the International Radiation Protection Association (INIRC IRPA - International Non-Ionizing Radiation Committee of International Radiation Protection Association), the Research Institute of Occupational Medicine of the Russian Academy of Medical Sciences, and others. The World Health Organization (WHO) coordinates these efforts toward the creation of uniform global standards. Currently, safety standards for some ranges can differ by tens or hundreds of times, indicating a lack of scientific research in this area.

They are studying the biological effects of devices whose “services” difficult to refuse: power lines, cars, televisions, background radiation from residential and industrial premises, most recently especially computers and cordless telephones. Some idea of the level of industrial frequency electromagnetic fields from power lines is given by Fig. 1.2, which shows the calculated distribution of electrical and magnetic fields depending on the distance to the line.

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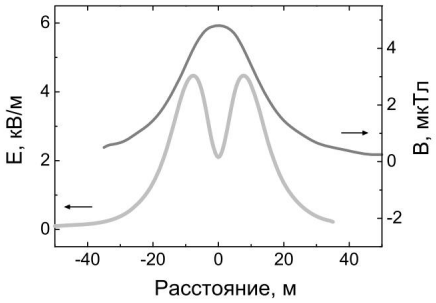


Fig. 1.3: Average profiles EMF at 1 m from the ground surface for standard 380 kV, 50 Hz lines under a load of 400 A, according to data [352].

The radiation fields of household appliances have been measured repeatedly. For example, measurements of 50 Hz MP carried out by Conti, Caracciolo and Sartore [352] at a distance of half a meter from household appliances showed the following roughly averaged values: washing machine - 5 ÿT, refrigerator - 0.1 ÿT, air conditioner - 1 ÿT, electric meat grinder - 2 ÿT, vacuum cleaner - 2 ÿT. Range ÿ 0.1–1 ÿT in order of magnitude typical for most office and public spaces and vehicles, although peak values can be three orders of magnitude higher more.

Distribution of background magnetic field intensity in the strip 30–2000 Hz in urban conditions (Goteborg City, Sweden) were studied by Lindgren et al. [419]. It turned out that up to 50% of the population is in in places where the magnetic field exceeds 0.2 ÿT and about 5% - 1 ÿT.

The biological significance of such electrical and magnetic fields have been identified in many epidemiological studies, see, for example, [694], the starting point of which is considered to be the work of Milham [573] mortality among workers with increased exposure to EMF. One Among the most recent reviews on this topic, Nakagawa [584] contains an analysis of 31 positive and 13 negative studies showing an increase in the relative risk of cancer of approximately twice for the population living near power lines and for workers engaged in energy-intensive industries. In all cases, the magnetic field level fell, on average, within the range of 0.1–10 ÿT. Grigoriev [66] notes the need for constant monitoring of electromagnetic background fields surrounding a person.

The issues of “electromagnetic weather”, the action of cosmic and geophysical electromagnetic factors, such as magnetic storms (0.1–1 ÿT), are already a regular topic of discussion at the International Congress on Biometeorology.

The harmful effects of EMF from electrical household appliances can

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may also be of an indirect nature. It is known, for example, that under normal conditions in the air of residential premises there is a certain natural concentration of aeroions due to the ionization of the air by the decay products of the radioactive gas radon. It is about several thousand ions per cm3. This natural factor is not indifferent to life [49]. The screen of a standard monitor, usually having

high positive potential, collects negative air ions and repels positive ones.4 This leads to complete
disappearance of air ions from the area of the personal computer operator [2]. Work at the monitor screen, which, in addition to indirect
actions, emits EMF in a wide range of frequencies, experts from the World Health Organization (WHO) consider it as one
from stress factors.

The relationship between EMF and cardiovascular risk is being intensively studied. diseases. In this regard, EMF and natural
origin, in particular the geomagnetic field (GMF).

The risk of cancer is being studied most extensively [457, 612, 570, 434]. There are several hundred publications on this topic [584]. The American Journal of Epidemiology recently devoted a collection of materials to just one section of this topic—EMF and brain tumors in children [539]. Some of the articles assert that the data do not support the hypothesis of the carcinogenic effect of magnetic fields from high-voltage lines, electric heaters, and other household appliances [702]. Another section notes the primitiveness of the assessment of the effectiveness
exposure to magnetic fields, possible systematic errors
control and the preliminary nature of these works, requiring subsequent discussions [345, 336].

It is assumed that chronic exposure to even weak fields
is capable of suppressing the activity of some clones of immune system cells and, thus, depriving the body of protection from reproduction
"foreign" cells [237, 687]. Another possible mechanism is associated with MP-induced changes at the genetic level [431]. Also
There is evidence that low-frequency magnetic fields can affect
the body to synthesize certain peptides that act as internal biological signals [456, 142]. Coghill [114] showed that the level of industrial frequency EM fields, both electric and magnetic, was approximately 1.3–2 times higher at the bedside of children,

patients with leukemia, compared to the field level at the bedside of healthy people

4Modern monitors are equipped with a special screen coating that significantly reduces containing electrostatic potential.

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children. For studies conducted in the UK, see *NRPB (National Radiological Protection Board) documents, Volume 12(1), 2001* or //, showed, that prolonged exposure to industrial frequency electromagnetic fields an average level of 0.4 ÿT correlates with a doubling of the risk of disease leukemia in children under 15 years of age. Novikov, Novikova and Kachan [146] report that weak MPs, under certain conditions, on the contrary, inhibit the cancer process.

The results of extensive, long-term studies of childhood cancer in Sweden and Denmark published the European Journal of Cancer in an article by Feting, Schulgen et al. [550]. The authors of this article conclude that Their data, on the contrary, confirm the hypothesis of a connection between the magnetic fields of high-voltage communications and childhood leukemia. One One of the consulting firms involved recently released a comprehensive analysis of the scientific literature on epidemiological studies of diseases related to electromagnetic pollution levels. Their handbook, Sage and Sampson [648], contains over 500 (!) observations and risk assessments regarding cancers and disorders the course of pregnancy during exposure to EMF in domestic and professional settings.

In 20% of the papers presented at the III Congress of the European Association for Bioelectromagnetism in 1996, the topic was discussed in one way or another. the problem of the relationship between cancer and electromagnetic radiation. On the one hand, it has been precisely established that EM fields in some in some cases, they enhance the carcinogenic effects of a number of harmful chemicals substances and other factors, Wilson, Stevens and Anderson [434]. For example, Jutiläinen, Kumlin et al. found that 50 Hz MF can accelerate development of skin cancer due to UV radiation [404]. It is known that MP changes the activity of the hormone melatonin, which carries out fine regulation of the body's immune system [347, 548, 430, 397, 405, 626, 500, 570, 469, 318]. On the other hand, there is no strict dependence on MP, In [569] no connection was found between 60 Hz MF and melatonin levels. Jutilainen, Lang, and Ritomaa [495] believe that the effects are most pronounced when exposure to both EM radiation and chemical carcinogens is chronic. Much remains unclear and These phenomena should be studied [629, 690].

It should be noted that such studies, especially of an epidemiological nature, are quite extensive abroad [243, 337]. Scientific societies have been created that receive government support. In addition, they show interest in and finance research in the field of electromagnetism.

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manufacturers of radio telephones and computers are starting to take electromagnetic radiation into account. Even real estate companies are starting to take electromagnetic radiation into account. factor in evaluating their objects [518]. At the same time, the American Cancer Society published
in his journal, Heath's article, a review of the results of epidemiological studies over 20 years [471], in which epidemiological data
The evidence for a link between EMFs and cancer is considered "weak, inconsistent, and inconclusive." We also note the special issue *of Bioelectromagnetics, Supplement 5, 2001,* which documents the current state of research on the link between background EMFs and cancer.

Despite the still generally negative attitude of physicists
With regard to the phenomena under discussion, the latest edition of the Physical Encyclopedia contains the following statement [64]: *Some variations of the geomagnetic field can have an effect on living organisms.*
we. Although this statement is not entirely correct5, the fact that the possibility of such influence is recognized is important. Relatively recently, in 1981, member Ph.D. USSR Academy of Sciences M.V. Wolkenstein wrote in his monograph “Biophysics”: *. . . there is still almost no reliable data on the impact of a constant magnetic field on biological phenomena.* After 10–15
For years, we have had a huge bank of information on magnetobiology. It should be noted that individual works in the field of magnetobiology have been published since the beginning of the century; see, for example, the brief review by Warnke and Popp [710].

The drama of the problem is amplified by negative statements from some sectors of the scientific community. In the leading American physics journal *Phys. Rev. A, 43(1991)1039* we read:
· · · any biological effects of weak low-frequency fields at the cellular level should be outside the scope of traditional physics... The American Physical Society has circulated a summary [674] expressing doubt about the advisability of budget expenditures in this area. National Academy of Sciences of the USA
in an attempt to develop some final opinion on this issue, a special commission was created. The report of this commission [614],
presenting a review of the majority of literary sources on the problem, on the contrary, raised numerous questions. Even the members of this commission had different points of view on the results of the review. A year later

5In the absence of a large group of direct experiments reliably confirming the biological action of a weak fluctuating component of the magnetic field, one should speak of *a correlation* variations in GMF and the vital activity of some organisms.

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same, upon completion of the multi-year research program RAPID6 US National Institute of Environmental Health and Safety (NIEHS) published an extensive report to the US Congress [253], including about ten sections on the problem. Reading the section on the biophysical mechanisms of magnetoreception leaves no doubt that professional physicists were practically not involved in the implementation of the program. According to the authors of the report, low-frequency magnetic fields can cause cancer in humans.

The reason for such a contradictory situation is the lack of understanding of the physical mechanisms of biochemical action of weak EMFs.

The general state of affairs in the field of electromagnetobiology, its "living nerve", is aptly reflected in the open letter of the presidents of the American Society of Bioelectromagnetics7 to the officials of the Chamber representatives and the US Senate, responsible for issues of the state budget and scientific and technological policy [543]. In view of the importance and A small translation of the letter (V.B.) is given in full:

Interest continues to grow in the possible link between radiation exposure electric and magnetic fields and childhood leukemia, respiratory cancer, and Alzheimer's disease. At the same time, daily population exposure to electric and magnetic fields is rapidly increasing.
magnetic fields due to the emergence of new electronic and communication technologies, new medical applications of electromagnetic fields, and the use of greater amounts of electricity. How
leaders of the largest international scientific society studying
biological effects of electric and magnetic fields, we are concerned about the potential decline in research intensity in this area, particularly due to public statements by individuals who we believe
there is a lack of necessary specialized interdisciplinary knowledge.

Biological processes in human diseases are complex and multifaceted. Moreover, electric and magnetic fields, unlike many other environmental factors, are characterized not only by
quantity, but also various other properties. Appropriate approaches to such complex scientific questions can only be achieved through interdisciplinary collaboration between biologists, physicians, engineers, and biophysicists. The abundance of published, peer-reviewed scientific evidence
indicates that exposure to various combinations of electrical and magnetic fields act in a coordinated manner on biological systems in in natural conditions, as well as in laboratories. This action includes tea:

6Research and Public Information Dissemination Program, see, for example, [580].

7The society unites more than 700 members from more than 30 countries.

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- changes in the function of nerve cells
- changes in bone density and healing rate
- imbalance of important hormones
- changes in the growth rate and sensitivity of cancer cells to chemicals
Czech drugs
- changes in the ability of the immune system to resist diseases
- change in heart rate.

There are both potential benefits from these fields and the possibility of harmful effects on public health. Understanding the mechanisms of their biological action may allow us to increase

benefit and mitigate potential danger. But these processes cannot
be well understood without further research.

Major advances in this area of research have been made in the last twenty years. The program has only recently acquired critical importance.
a lot of interdisciplinary and interlaboratory efforts, which, in our opinion,
In my opinion, this should be continued. In this still-expanding field of scientific research, discrepancies in published results are a natural and necessary part of the scientific process.

Such discrepancies cannot be the basis for discontinuing the research program until final answers are obtained.
important questions.

We believe that it is extremely important to continue the work.
Without US government financial support, the remaining available funding sources are too limited, too specialized, and
may lead to deviation from the correct scientific direction. Governments of other industrialized countries, such as Sweden, Japan,
Germany and Norway are currently spending significant amounts of money on further research in this area. But without
the coordinating role of the United States in the task of identifying potential benefits and health risks from the distribution and use of electrical and magnetic energy will be difficult to end.

We are also concerned that relevant international standards may be introduced before the necessary scientific knowledge is available. Halting this research could ultimately lead to unnecessary legal costs.

to energy and communications companies.

Public concern could be reduced only after the issues and problems of electromagnetobiology are resolved through careful
research. We propose that this information be taken into account when making decisions regarding future research on biological effects.
electric and magnetic fields. The undersigned will be happy to discuss in detail or provide any necessary information,
which may be required to make an informed decision.

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Richard A. Luben, BEMS President, 1996-97
Kjell Hansson Mild, BEMS President, 1995-96
Martin Blank, BEMS President, 1997-98

The number of reviews of experimental work on magnetobiology, various manuals, reports and books is large and continues to grow. Brief and an incomplete list of them could include works [163, 161, 434, 542, 610, 662, 283, 239, 264, 417, 473, 453, 466, 476, 647, 310, 433, 308, 311, 570, 634]. Review academic publications also appear [309, 302].

A good introduction to electromagnetobiology can be considered the thousand-page collection of proceedings of the Second World Congress on Electricity and Magnetism in Biology and Medicine [410], edited Bersani. This 1999 book contains more than 230 articles on various issues in this field of science, from fundamental physical and biological to socio-political. There is an electronic bank data // on all aspects of electromagnetic biology, scientific, medical, social, which contains about 30,000 bibliographic units. Addresses of open bibliographic databases on individual areas of magnetobiology can be found at //. An interesting essay on the history of the development of electromagnetic biology is contained in Kholodov's monograph [203].

Ten years ago, in 1986, it was already reported about the analysis of more than 6000 literary sources on this topic [510]. Recently in the world Several thousand articles on electromagnetic biology are published annually, see Fig. 5.19. Historical review of Russian, mainly experimental work is given in a recent publication by Zhadin [733].

At the same time, critical reviews of theoretical works are virtually nonexistent, primarily due to the lack of theoretical works themselves. There are a few articles that contain a critical analysis from a physical perspective of known ideas about the mechanisms of action of magnetic resonance. [119, 36, 235, 301]. The main reviews that appear are those that are reduced to the fixation of ideas [241, 610, 568, 283]. There are only a few controversial attempts to provide a physical justification for some reliably reproducible experiments with weak MFs [576, 305]. These models, at least at first glance, do not contradict either the orthodox neither physics nor common sense.

Research into ways to protect against the harmful effects of EMFs is growing. The most complete protection is possible only in natural environments. conditions - away from cities, where the level of electromagnetic pollution is approximately three orders of magnitude less than in the city, Fig. 1.4. Max-

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Maximum magnetic variations of man-made origin are observed in the z-component of the magnetic field inside trams, trains, and near other
power plants [55]. These variations in the 0.05–0.2 Hz band can
exceed the amplitude of a strong magnetic storm by a thousand times.

General measures are known to reduce the risk of diseases due to excessive EMF exposure is to reduce the level of electromagnetic pollution. The difficulty here is as follows. Biological systems themselves are sources of electromagnetic
fields [204], their development for thousands of years took place against the background of the Earth's natural electromagnetic field. Therefore, EMFs as such are not a harmful factor for humans. Certain fields of the natural level and spectrum are useful and even necessary for normal
life. In addition, there are many effective treatment procedures using EM radiation [231]. Purely practical conscious experience of using electricity and magnetism can be traced back to 1270, [680]. Fundamental works of Academician Devyatkov in
The fields of microwave technology have become the basis for the medical application of these electromagnetic radiations. In Russia alone, more than Thousands of medical institutions use about a hundred different modifications of UHF therapy devices. Over several decades
More than a million patients have undergone successful treatment; up to fifty diseases can be cured [307].

The use of microwave, laser and other radiation to ensure human health is often called quantum medicine, having
due to the targeted exposure to small doses of EM radiation, i.e.
quanta, for the treatment, diagnosis, prevention and rehabilitation of patients [65, 177], //. The authors of the indicated works believe that the interaction of EM fields and living systems should be described
in terms of quantum mechanics.

Magnetic therapy has received significant development in the world [232, 262]. It is known that low-frequency EM fields, for example, promote the healing of bone fractures in difficult situations [645]. In a number of cases
preliminary exposure of the body to a weak low-frequency magnetic field allows to significantly increase its resistance to unfavorable external factors [118]. At the same time, the high therapeutic effectiveness of EMF indicates their potential danger. There is an analogy here with the use of chemical drugs. Medicines that are useful in certain doses become dangerous under conditions of their uncontrolled and chronic exposure. Therefore, reducing the risk of diseases due to electromagnetic pollution is

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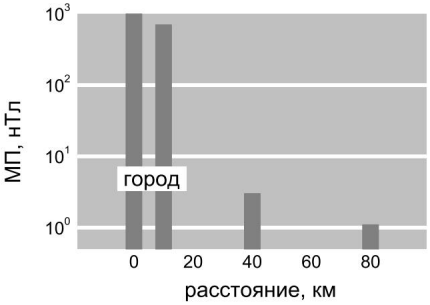


Fig. 1.4: Average intensity of vertical variations components of the magnetic field in in the range of 10ÿ3–10 Hz in St. Petersburg and its environs NW–SE lines. According to [55].

complex scientific and technical problem. Sanitary safety standards electromagnetic radiation is regulated in Russia by GOST R 50949-96 and SNiP 2.2.2.542-96. Among foreign standards, the following are known: MPR-II, MPR-III, TCO 95-96 and a number of others.

A promising direction for reducing the risk of diseases, in addition to general reduction of the level of electromagnetic pollution, is use... electromagnetic fields! Just as homeopathic ultra-low doses of substances are capable of paradoxically compensating for the biological action of the same substances in normal doses, the action weak harmful EMFs could be compensated by similar fields, only even weaker. Devices implementing This principle was presented at the Congress of the European Bioelectromagnetic Association in Nancy, 1996. Research by a number of scientific groups coordinated by M. Fillon-Robin showed that these devices reduce the risk of disease when using computer monitors and cell phones [413].

There is also direct evidence that experimental MPs of a special type are capable of leading to a slowdown in the growth and even the resorption of cancerous tumors, Muzalevskaya and Uritsky [140]. In the work [60] Garkavi, Kvakina and Shikhlyarova report a slowdown in the growth of sarcoma in rats when exposed to MF with a spectrum in the low-frequency range, Fig. 1.5.

It will probably soon be possible to explain the effectiveness of low-frequency Geomagnetic electromagnetic fields. The biological effects of geomagnetic field fluctuations are currently far less well understood.

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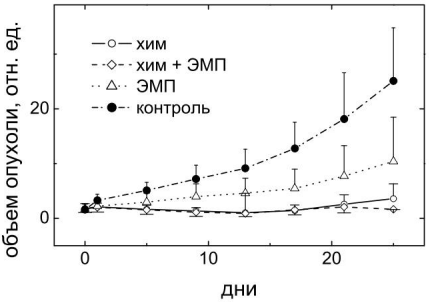


Fig. 1.5: Growth of transplantable sarcoma in male rats under separate and combined action
cyclophosphamide and MP 1 mT. By data [60].

1.2 Statistical data

The statistics of research in the field of magnetobiology and electromagnetobiology, of which it is a part, are interesting. Over the decades of development of this science, the flow of publications has increased many times over and now amounts to thousands of articles and reports per year. To get an idea of
The analysis of the proceedings of the largest symposia, congresses and conferences devoted to the problems of electromagnetobiology helps to understand the global distribution of these works, as well as the internal structure of the research.

Thus, the third international congress of the European Association for
The EBEA, held in Nancy, France in the spring of 1996, brought together participants from 27 countries. They presented
about two hundred papers. The contributions of individual countries to this volume vary significantly, so Figure 1.6 can be used to judge the intensity of work on electromagnetic biology in different countries of the world. Shown are the absolute contributions, in terms of the number of reports submitted, and the relative contributions, in relation to the country's population in millions of people.
countries. On average, one report per two million population was submitted to the Congress. The relatively even trend in relative contributions is noteworthy. This suggests that the problems
potential danger of electromagnetic pollution, the interaction of EM fields and the biosphere as a whole, represent a common problem in
on a global scale.

Figure 1.7 shows the percentage of work in one direction or another in electromagnetic biology. Experimental work is carried out approximately equally on dissected living

tissues, cells, proteins, and over entire biological and social units, including humans. Engineering calculations of EM field distributions clearly predominate in the theoretical part of the work.
in the surrounding natural and artificial environment, as well as in tissues

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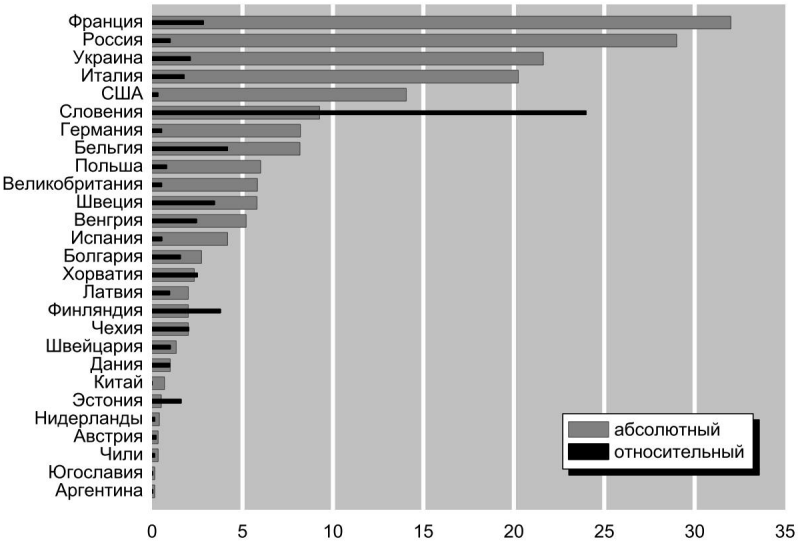


Figure 1.6: Absolute (number of contributions) and relative contributions of different countries to the proceedings of the III EBEA Congress, 1996.

animals and humans. A lot of calculations are related to radiation
cellular radiotelephones near the user's head. The lack of fruitful physical ideas about the primary mechanisms of magnetoreception8
determines the small number of works on the fundamental question for magnetobiology about the nature of biomagnetic reception. This circumstance
is connected, as already mentioned, with the paradoxical nature of magnetobiological effects. The paradoxical nature is especially evident in experiments with low-frequency EM fields, when the energy quantum
fields are approximately ten orders of magnitude smaller than the characteristic energy chemical bonds. There is still no generally accepted mechanism for the biological action of such fields. Apparently, this is precisely what
as well as the availability and ease of generating artificial fields in the low-frequency range lead to a relatively large number of experiments in this area.

Since 1983, symposiums dedicated to research into the correlation of various physical, chemical and biological processes have been held in Pushchino.

8The term magnetoreception is used throughout the book in a broad sense, as a way-the ability of living systems to respond to changes in magnetic fields.

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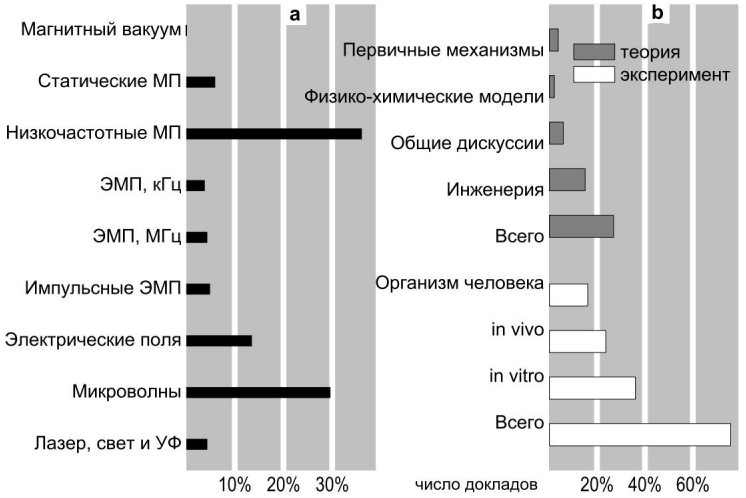


Fig. 1.7: Structure of papers presented at the III EBEA Congress.
Number of works in this direction as a % of the number of submitted works:
a — range of electromagnetic fields, b — nature of work.

processes with cosmophysical processes [216]. It is noteworthy that of 57 articles published based on the proceedings of the 1990 symposium [133], 40% of the articles in one way or another contain a discussion of the connection between biospheric processes and geomagnetic disturbances. Of the 65 articles in the 1993 symposium [134], the number of such reports increased to 55%.

Researchers from 35 countries took part in the II World Congress on Electricity and Magnetism in Biology and Medicine.
Over 600 papers were presented, Fig. 1.8. The congress covered issues of biology, medicine, technology and physics related to various manifestations of electromagnetic biology. Discussions were grouped on several topics: biophysical mechanisms of the phenomenon, bioenergetics and electron transfer, transmission of biological signals, sensory physiology, effects of microwaves, electromagnetic epidemiology, assessment of radiation levels, bioeffects of cell phones, bioelectronic devices and biocomputers, effects on bones and cartilage, electrical injuries and electrical treatment, electrically induced transport of drugs and genes, thermal effects of EMF, secretion of melatonin and

the effect of EMF on the immune and nervous systems, power lines and standards for permissible doses of radiation, the effects of permanent magnetic

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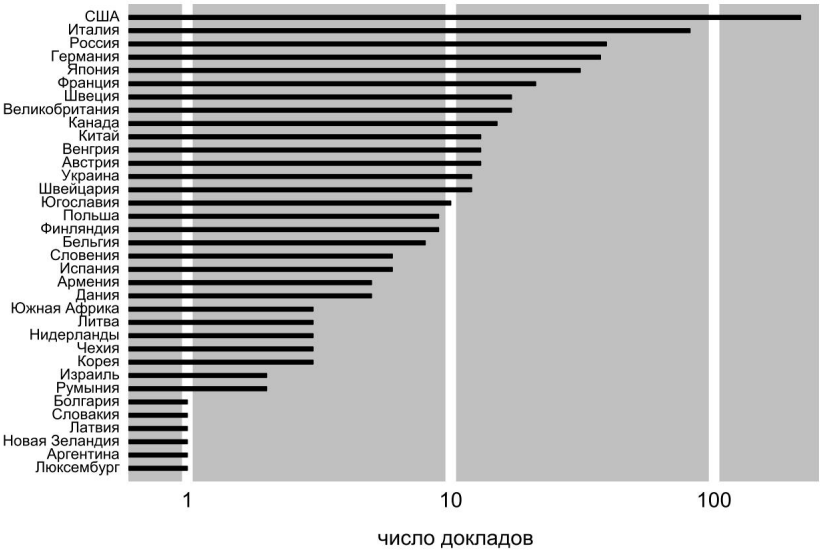


Fig. 1.8: Distribution of papers presented at the II World Congress on Electricity and Magnetism in Biology and Medicine, Bologna, 1997.

field, learning and memory for electromagnetic effects. The Congressional co-sponsors included, in addition to US government institutions, and Italy, a number of industrial corporations associated with production and distribution of electricity, and well-known manufacturing companies cellular radiotelephones.

An interesting event was the international congress “Weak and ultra-weak fields and radiation in biology and medicine”, which took place in the summer of 1997 in St. Petersburg [231]. Of the 352 reports presented at the congress, 223 were related to electromagnetobiology.

The structure of the congress messages will be determined by the number of reports on a particular topic or topic. another topic:

ultra-low field intensities	3
constant fields	13
electric fields, ELF range,	3
EMF, combined AC–DC	41
fields, extreme dose dependencies	5
	3

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MHz range of	4
UHF-microwave range of	41
IR, optical and UV range of EMF target	20
	1
computer models	3
analytical models and estimates	9
water systems	10
Engineering and technical developments,	38
general topics, ideas, hypotheses,	19
reports with deviations from scientific methodology	59

The assignment of reports to topics was sometimes definitely subjective, but such reports made up no more than 2–3%. It is noteworthy that
There are relatively few analytical studies into the mechanisms of action of EMFs. This is probably due to the uncertainty of the targets of such action. Only one study indicates a possible
The magnetic field target in living tissue. There are almost no reports on the control of static magnetic fields, with the exception, of course, of reports on the bioeffects of constant fields themselves. A large proportion of these studies are speculative, lacking factual data or making assertions that are fundamentally unverifiable.

It is significant that there are practically no messages that fall within the framework analytical reviews presented in Chapters 2 and 3. Most of the experimental reports presented were not aimed at testing any hypothesis, although ambiguity in the mechanisms of action was almost always noted. Therefore, there are multiple, often duplicative studies that cannot be commented on

point of view of physics. They contain, in essence, only confirmation of the facts of the biological effectiveness of EMF. Of course, expanding the factual base is valuable, especially in the medical aspect. At the same time
At present, the material accumulated in the world already allows us to plan special experiments aimed at clarifying the primary mechanisms of electro- and magnetoreception.

1.3 Methodological notes and terms

When describing real quantum physical processes, they use
a well-developed apparatus of quantum mechanics and quantum electrodynamics. Various processes require the use of mathematical tools of quantum mechanics and electrodynamics at different levels.

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depth and complexity. The phenomena studied in this work do not require special mathematical techniques. This is due to the fact that the subject of the study itself, the primary mechanisms of biomagnetic reception, a relatively new and undeveloped area of physics. Therefore, At this first stage of studying magnetobiological effects, the mathematical apparatus of quantum mechanics turns out to be sufficient level of depth that is typical of most university courses and is presented, for example, in the well-known monographs of L.D. Landau and E.M. Lifshitz [122], D.I. Blokhintsev [30], A.S. Davydov [70] and others.

In commenting on the physical nature of the phenomenon of biological effectiveness of MP, the terms "mechanism" and "model" are used, which are close in meaning but have a certain difference. The term "mechanism" is used when talking about a concept, about physical processes or their sequence, possibly underlying basis of the phenomenon. If it is necessary to emphasize that a given mechanism is embodied or realized in the form of equations or other mathematical relationships that have predictive power, the term is used "model". There may be none, or, conversely, there may be several mathematical models of the same mechanism of biological effectiveness of MP.

In some cases, for the sake of brevity, the term "atom" is used charged particle in a central potential, not electrons in a field nuclei. The analogy here is obvious.

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1.3.1 Designations and terms for magnetic fields

In the literature, to characterize the conditions for conducting magnetobiological experiments, the value of the magnetic field strength H is used, and the magnitude of the magnetic field induction B. The latter is related to H by the relation $B = \mu H$. Here μ is the magnetic permeability of the medium, generally speaking, has the character of a quantity that is an average value over a physically small volume of the medium. This is so because in B, in addition to H, there is contribution from the induced H magnetization of the medium. The latter is spoken of only in the sense of an average over a sufficiently large volume, when local inhomogeneities of the magnetic field of atomic sources, that is, the magnetic moments of the orbital motion of electrons, as well as unpaired spins of electrons and spins of nuclei, are smoothed out to a significant extent.

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Obviously, when considering the primary mechanisms of magnetoreception, when studying the movement of particles precisely on the atomic scale, it is more correct to use the value H, rather than B. Considering that the magnetic permeability of biological tissues is close in the Gaussian system
to unity [153], the atomic field H, on average over a physically small volume, practically coincides with the exogenous field, i.e., the field given
external sources: permanent magnets, Helmholtz rings
tsa and others.

However, some authors use the MKS system, where vacuum has magnetic permeability. Therefore, even to describe the motion of particles in a vacuum, for example, on the interatomic scale, it is necessary to use magnetic induction B. In this system, the unit of measurement of B is the Tesla (T), related to the unit of measurement of B in

the Gaussian system (G) with the ratio 1 G = 10ÿ4 T. In the Gaussian system, the magnetic field strength H is measured in Oersteds (Oe). Since
in this system ÿ is equal to one and, in addition, the quantity is dimensionless,
the units E and G are actually the same: 1 E = 1 G = 1 cmÿ1/2 g1/2 sÿ1.

In connection with the above circumstances, in the text of this work both H and B will be used to characterize MP. We emphasize that
In the latter case, it does not mean the presence of macroscopic magnetization in living tissue, but only the desire to use the units of MKS, T and ÿT (ÿT), which are convenient for many reasons.
In essence, we are almost always talking about a magnetic field in a vacuum, which is created by external sources.

The relationships between physical quantities in the book are given in the Gauss system of units.

Some organisms are not indifferent to the compensation of natural
local constant magnetic field up to the level of 1 G. To designate such
situations where the constant magnetic field takes on values that are small enough to cause a biological response, but which do not have a clear
boundaries, we will use the terms used in literature
"magnetic vacuum" and "zero field", leaving them without quotation marks. The formal definition of the conditions of magnetic vacuum, in biological
in the sense, we will consider inequalities

$$HAC \; HDC \; Hgeo ,$$

where Hgeo is a natural magnetic biological reference point, local
geomagnetic field.

One of the frequently used configurations of magnetic fields in experiments is the superposition of collinear constant and alternating magnetic fields.

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fields. Since the direction of the magnetic field vector does not change over time, such a configuration is conventionally designated as a "uniaxial magnetic field." In the more general case of a superposition of arbitrarily oriented constant and alternating magnetic fields, we will speak of about "combined MP".

In the literature, the following terms are used to designate the frequency ranges of fields: low (LF) 30–300 kHz, very low (VLF) 3–30 kHz, infra-low (ILF) 0.3–3 kHz, ultra-low (ULF) 30–300 Hz and extremely low frequencies (LLF) 3–30 Hz. Since from the point of view of the primary physical mechanisms of biological effectiveness of MPs, there are no significant There are no differences between these ranges; for convenience, the book uses the single term “low-frequency MP”.

The magnetic field values are defined below in relation to the natural level of the geomagnetic field for biology of ÿ 50 ÿT. For For such fields, however, in the absence of clear boundaries, the term "weak MF" is used in the literature. Fields exceeding 1 mT will be defined as "strong MF." Accordingly, fields less than 1 ÿT are defined as "ultraweak MF." In the literature on magnetobiology, it is often use the term "amplitude" in relation to a sinusoidal signal in a broad sense, each time specifying what exactly they mean, peak value, rms value or difference between the maximum and minimum values (peak-to-peak value). In this book, the term is retained in its strict meaning, that is, there is, the maximum or peak value of the signal.

In a number of cases, the term “power” is used for convenience in a broad sense, in relation to energy flow density and other energy characteristics of electromagnetic radiation, which will It is clear from the context.

1.4 Magnetobiological effect

The term "magnetobiological effect" or MBE for short, used in the book, has the following meaning. On the one hand, the term denotes any change in any properties of a biological system caused by a change in the magnetic conditions of its existence. These may be biological properties of the organism in vivo or biochemical parameters of a living system in vitro.

Biophysical structures at the micro level are common to most living systems - these are proteins, membranes, etc. It is clear that the primary mechanism of magnetoreception, realized at the level of bio-

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physical structures, have the same commonality. But one and the same the same primary mechanism in various types of biological systems can manifest itself in changing a wide variety of properties.

From the point of view of studying the primary mechanism, biological systems are only special tools for its research.
In this sense, all biological systems that exhibit magnetosensitivity are the same. It is important that the nature of the change in a property depending on varying magnetic conditions allows us to extract information about the nature of primary magnetoreception.
It matters which property changes in the system. Therefore,
It is convenient to talk about the “magnetobiological effect” when referring only to dependence on the parameters of the MP and abstracting from the biological embodiment of this dependence.

On the other hand, this term, in the physical plane, distinguishes
Magnetic conditions from the general electromagnetic environment. Comments are needed here. It is known that electromagnetic fields cause biological effects over a wide range of amplitudes, frequencies, etc. For example, sufficiently powerful EMFs generate conduction currents, heating in biological tissues, and also rotation of molecular dipoles. They cause significant shifts in many reactions and lead to pronounced biological effects. Thermal and electrochemical effects

are widely used in practice, including medical: UHF therapy, electrophoresis, etc. These phenomena are understandable and explainable in terms of
physics. On the contrary, the biological action of constants is paradoxical
MF, low-frequency variable MF, centimeter and millimeter waves of non-thermal intensity. At the same time, as variable
Both low-frequency magnetic fields and microwaves can have a significant electrical component. The question of its role in biological effects
The electromagnetic field of these ranges is complex. Experiments and theoretical analyses of the effects of weak low-frequency magnetic fields typically neglect the electrical component.

With the increase in the frequency of low-frequency magnetic resonance, sooner or later it is necessary take into account the induced electrical component, since it is proportional to the field frequency. The possibility of neglecting the electrical component also depends on the specific experimental implementation of the EMF source, the presence of a "near" or "far" zone configuration relative to the source. As the EMF intensity decreases

or with increasing frequency there comes a point when quantum electrodynamics becomes an adequate description of it. The language of electromagnetic
waves are replaced by the language of field quanta. The division of EMF into magnetic and

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electrical components becomes impossible. Thus,
the criteria of "magnetism" of the electromagnetic field determine the boundaries
magnetobiology as such and therefore require clarification.

1.4.1 Evaluation of the thermal effect of eddy currents

Changes in magnetic field over time induce an electric field. If in magnetic field
When a medium with electrical conductivity, such as a biological system, is placed in it, macroscopic currents arise. Their electrochemical action (that is, at the phase boundary and involving charge carriers) can cause a biological reaction. The reaction can also occur as a result of tissue heating due to Joule heating. The biological response in this case is not related to magnetobiology, since

as the magnetic field here is only one of the possible heating factors or sources of emf. On the other hand, it is obvious that such a response is a biological effect of the magnetic field. Thus, there is a significant difference between the biological effects of magnetic fields in general and the magnetobiological effect,
which appeals to special non-thermal and non-electrochemical
mechanisms of interaction between the MP and the biological system.

Let's estimate the boundary between the magnetobiological and thermal effects of magnetic fields. Since biological tissue is macroscopically neutral, Maxwell's equations for the electric field look like this:

$$\text{rotE} = -\frac{1}{c}\frac{\ddot{y}}{\ddot{y}t}B, \qquad \text{divD} = 0;$$

$$\text{rotH} = j, \quad \frac{4\ddot{y}}{c} \qquad \text{divB} = 0;$$

$$D = \ddot{y}E \quad , \quad B = \ddot{y}H \, , \; j = \ddot{y}E \, .$$

Let's rewrite them as

$$\text{rotE} = -\frac{1}{c}\frac{\ddot{y}}{(B + \text{Bind}) \, , \ddot{y}tc} \qquad \text{divE} = 0;$$

$$\text{rot}\,(B + \text{Bind}) = j \, , \; j = \ddot{y}E\frac{\ddot{y}4\ddot{y}}{c} \qquad ,$$

where B is the external homogeneous magnetic field, Bind is the magnetic field induced by the vortex with currents.

From the equations it is clear that the order of magnitude of the electric field, induced by a sinusoidal field B with frequency ÿ is rÿB/c.
The electric field induces a current of density ÿrÿB/c. In turn,

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This current creates a magnetic field equal to

$$\text{Bind } \ddot{y} \quad \frac{4\ddot{y}r2\ddot{y}\ddot{y}\ddot{y}}{c2} B.$$

The proportionality coefficient for the “biological” values of the parameters r ÿ 1 cm and ÿ ÿ 9 · 109 CGS units is much less than unity, i.e.
Bind B up to frequencies in the megahertz range. Therefore, further we will use equations

$$\text{rotE} = \quad -1 \frac{\ddot{y}}{c \ddot{y}tB}, \qquad \text{divE} = 0$$

and neglect the effects associated with the induction of magnetic fields by eddy currents, in particular, the skin effect. The last equation implies the solenoidality of the field E. In this case, it can be represented as
curl of a certain vector field, [512]

$$E(r) = \text{rot } 4\ddot{y} \frac{1}{} \qquad \frac{\text{rotE}(r)}{|r \ddot{y} r|} dv ,$$

over all points r . The formula defines the induced integration field E by its curl in an arbitrary coordinate system with an accuracy of up to the gradient of some potential ÿ satisfying the condition div(gradÿ)=0. It is simpler, however, to calculate the field E, guided by
considerations of symmetry and by choosing appropriate EMF potentials.

Let a uniform magnetic field B be directed along the z-axis and limited by the dimensions of an infinitely long solenoid—an idealization often used in calculations. Then the field E has only an angular (tangential) component. Potentials can be chosen in the form

$$A(r) = B \times \frac{1}{2} r, A0 = 0 .$$

It is easy to verify that B = rotA, as it should be. Since E(r)= $\ddot{y}\text{grad}A0 \ddot{y} \ddot{y}tA(r)$, then, moving to a cylindrical coordinate system, we find9

$$E\ddot{y} = \ddot{y} 2c \quad \frac{r}{} \frac{\ddot{y}}{\ddot{y}tB(t)} .$$

Note that for the chosen potential calibration E(0) = 0. That is,
Yes, such calibration is only possible in the center coordinate system

9In convenient units, this ratio can be written as Epeak[ÿV/m]= 0.01ÿr[cm] f[Hz] Bpeak[ÿT], [575].

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symmetry of the magnetic field sources, the condition of magnetic field homogeneity alone is not sufficient to obtain Eÿ . Accordingly, r here is the distance from center of the solenoid.

On the other hand, the Joule thermal energy of a current with density j = ÿE, released per unit of time in a unit of volume is equal to

$$w = ÿE2 \quad ,$$

where ÿ is the specific electrical conductivity of the medium. From here it is easy find the average energy released per unit time in a macroscopic section of the medium of radius R and height a, which is placed in the center solenoid. This will be a model of a biological body. We write down

$$\int w\,dv = a\,ÿE2\,ÿ2ÿr\,dr = \frac{ÿ}{8}\frac{aÿR4}{c2}\overline{\left(\frac{ÿ}{ÿtB(t)}\right)^2} = \frac{ÿ}{16}\frac{aÿR4}{c2}B2ÿ2 .$$

The last equality takes into account that the MP is sinusoidal, B(t)= B cos(ÿt), and the relation sin2(ÿt)= 1 holds. $\overline{2}$. Thus, in On average, per unit volume of a body (V = aÿR2) there is power

$$P = \frac{ÿR2}{16c2}B2ÿ2 .$$

It depends on the size of the body, which is a consequence of the proportionality of Eÿ to the distance r to the center of the solenoid.

The increase in temperature T of a body due to the transfer of heat Q to it equals

$$dT = \frac{1}{cQ}dQ ,$$

where cQ is the heat capacity per unit volume. Taking the derivative with respect to time from this equality, we obtain

$$T_t = \frac{1}{cQ}P,$$

that after substituting the expression for P leads to a dependence of the MF amplitude on frequency, which determines the boundary of thermal effects on the amplitude-frequency plane, Fig. 3.1 (Chapter 3).

$$B = \frac{4c}{R}\sqrt{\frac{T\,tcQ}{ÿ}}\frac{1}{ÿ} . \qquad (1.1)$$

Note that with any complex geometry of the body and non-uniform distribution of electrical conductivity and heat capacity over

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volume, which almost always occurs in an experiment, the corresponding calculations are much more complicated and require special numerical methods, see, for example, the work of Gandhi et al. [361]. Therefore, the assessment of orders of magnitude in this case is entirely justified.

Let us accept the following values of the parameters of biological tissue and sample dimensions: ÿ ÿ 1 S/m = 9·109 CGS units [560, 438, 443], cQ ÿ 1 cal/(cm3 deg) ÿ 4.2 107 erg/(cm3 deg), R ÿ 1 cm. We will take the temperature increase as a criterion for the biological significance of tissue heating. process with a $_t$ ÿ 0.1 deg/min (in the absence of heat removal). Then the proportionality between B and ÿ in Gaussian units has $^{-1}$ view

$$B \ddot{y} 108 / f . \qquad (1.2)$$

The relationship is valid as long as the conductivity can be considered independent of frequency. As frequency increases, a contribution to the conductivity and Joule heating appears due to the imaginary component of the complex permittivity of the medium, that is, polarization currents. Conductivity increases, so the boundary of the thermal values of the amplitude B decreases compared to the predictions (1.2). This the reduction may begin already at frequencies of ÿ 1 kHz. Since the static the dielectric constant of biological tissue is no more than 100, then the indicated reduction does not exceed one or two orders of magnitude and is almost unnoticeable on the scale of Fig. 3.1. Note that dependence (1.2) determines the boundary of thermal effects approximately, with an accuracy of two or three orders. Therefore, in each specific case, if necessary, it must be calculated separately.

■ Sometimes, as a criterion for the biological significance of eddy currents, a current density of ÿ 1 mA/m2 [584] is taken, on the order of the density natural biocurrents, starting from which electrochemical reactions of living tissue arise. In this case, the dependence linking the amplitude of the MF with its frequency, calculated by analogy with (1.2), has view

$$B \ddot{y} 6 \cdot 102 f \frac{1}{}, \qquad (1.3)$$

that is, five orders of magnitude lower than the thermal threshold adopted above. This dependence, part of the broken curve in Fig. 3.1, adopted by the American Conference on Industrial Hygiene (on Governmental Industrial Hygienists) as the safety boundary of low-frequency MF. In particular, at a frequency of 50 Hz it gives a threshold level of about 12 Gs. Note that this is one to two orders of magnitude higher than the field levels reliably measured in the laboratory for a number of

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magnetobiological effects. Standards of similar order of magnitude established by other organizations [141].

1.4.2 Criterion of classical electromagnetic field la

In [15] a criterion for the applicability of the classical description of EMF is given. It relies on the requirement of large quantum numbers of elementary particles. EMF oscillators in a quantum description. The criterion relates the frequency f and the amplitude of the magnetic H or electric E component of the alternating field:10

$$H \ddot{y} c \quad — \quad \frac{f}{c}^{2} \quad \ddot{y} \; 10\ddot{y}29f\,2 \quad , \qquad (1.4)$$

where the numerical coefficient is written in the CGS system. This can be illustrated as follows. The energy flux density of the electromagnetic field plane wave is related to the magnitude of the magnetic field by the relation (1.9): S = cH2/4ÿ. Therefore, in a volume ÿ3, where ÿ = c/f is the wavelength, there are about Sÿ2 ÿ $\frac{}{c}$ energy. At the same time, ÿ3 is a characteristic volume of a quantum of EM radiation with a wavelength ÿ. It is clear that the classical description is valid if the number of field quanta 2ÿf in the volume ÿ3 is much greater than unity. That is, Sÿ3/c >> 2ÿf. From this we obtain an inequality that, up to a numerical coefficient of order units repeats (1.4).

Note that criterion (1.4) is of a very conditional nature, it assumes isotropy and a fairly wide spectrum (ÿf ÿ f) of radiation. There is no point in talking about accuracy here—the accuracy is certainly no better than several orders of magnitude. If there is anisotropy and a narrow spectrum, as in laser radiation, then the ratio becomes more certain.

The number of field oscillators with an absolute value of the wave number k (k = 2ÿf /c) in the interval ÿk, direction in the element of solid angles ÿo per unit volume is equal to ([121], p. 166)

$$\frac{\ddot{y}o}{(2\ddot{y})3}\,k2\ddot{y}k.$$

Considering that the energy of the electromagnetic field per unit volume is S/c, we obtain the number quanta of the oscillator, dividing this energy by the number of oscillators and by

10In the Gaussian system, the dimensions of E and H are equal to g1/2cmÿ1/2sÿ1.

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photon energy 2ÿf:

$$\frac{Sc2}{2\ddot{y}\ddot{y}f\ \ddot{y}of^{4}}.$$

The classical consideration is admissible provided that the number of quanta is large. From this we obtain a limit on the radiation power density

$$S\ \ddot{y}o\ddot{y}f \qquad \frac{2\ddot{y}}{c2}f^{4}. \tag{1.5}$$

For example, for a gas-discharge laser, the angular beam width depends on wavelength and dimensions L of the resonator: ÿ ÿ ÿ/L, so that the solid The radiation angle ÿo ÿ 10ÿ6 sr. The relative width of the spectral line, ÿf ÿ 10ÿ9, is determined mainly by the Doppler effect.
A wavelength of about 1 μm corresponds to a frequency of f = 3 · 1014 Hz. From (1.5) we obtain S 10ÿ4 erg/cm2c = 10ÿ8 mW/cm2. Since the power density of, for example, a helium-neon laser is about
1 W/cm2, then its radiation can be considered with a large reserve like a classical field.

For isotropic broadband radiation it follows formally put ÿo ÿ 1, ÿf ÿ 1. Then, taking into account the relation S = cH2/4ÿ, (1.5) returns criterion (1.4).

As can be seen from (1.4), in the region of low-frequency magnetic fields down to vanishingly small amplitudes, the classical description of the electromagnetic field is suitable. Dependence (1.4), which determines the regions classical and quantum description of EMF on the amplitude plane frequency, is also shown in Fig. 3.1. Together with curve (1.2), it highlights the area of magnetobiology, which by definition should be the area of non-thermal effects and at the same time the area of classical description of EMF, when it is permissible to isolate the magnetic component you fields.

The quantum dynamics of particles in classical EMF constitutes the so-called semi-classical approximation. In this approximation, the dynamic The particle equation has the form of the Schrödinger equation, in the broad sense, and the electromagnetic field enters the equation in the form of the vector A and scalar A0 potentials of the electromagnetic field. The potentials are defined up to a gauge transformation: for important special cases of an external homogeneous alternating magnetic field and a plane electromagnetic wave, the fields H and E can be defined simply through the vector potential, setting A0 = 0.
Then the question of which field determines the motion of a particle, magnetic or electric, becomes meaningless. From a general point of view, the determining factor is the vector potential of the electromagnetic field, and there are no restrictions on

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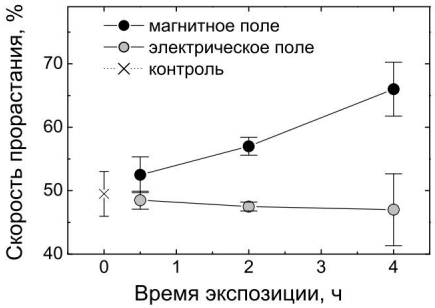


Fig. 1.9: Germination of mushrooms cells in magnetic and electric fields frequency modulated (10 Hz) 150 MHz EMF depending on time exposure.

frequency or amplitude of the field, other than the indicated quantum electrodynamic, is not observed. If, however, we keep in mind some mechanisms defined below, within the framework of the general semi-classical descriptions, they highlight areas of their possible effectiveness on the frequency-amplitude plane of EMF parameters.

For a non-plane wave, in the near zone of the emitter, in some cases it is possible to create a purely electric or purely magnetic alternating field, to a certain degree of accuracy. Thus, Broers, Kraepelin, and others in the work [583] used a 150 MHz cylindrical resonator shape, about one and a half meters in size. Standing electric and magnetic waves in such a resonator form nodes and antinodes. For the placement of the cell culture of the fungus *M. africana* in the resonator, we selected places with a purely magnetic (1.2 nT at maximum), within the accuracy of the experiment, or with a purely electric (0.91 V/m) wave. The results shown in Fig. 1.9 show that the magnetic field, in

Unlike electrical, it resulted in a statistically significant biological effect.

It is interesting to plot the areas of parameter changes on graph 3.1 EMF as a classical wave corresponding to some processes and experiments.

It is known that the sensitivity threshold of the human eye is about N = 10 photons during the eye reaction time ÿ ÿ 0.1 s [541]. We assume that that photons correspond to the maximum spectral sensitivity eyes, that is, the wavelength is equal to ÿ = 55.5·10ÿ6 cm. Then it is easy to find that the quantum energy is 2ÿc/ÿ, and the energy flux density through the pupil area is ÿ 1 cm2

$$\frac{1}{\ddot{y}} N \, 2\ddot{y} \quad \frac{c}{\ddot{y}} \frac{1}{-} .$$

On the other hand, the energy flux density of a plane wave is related to

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the amplitude of its magnetic component by relation (1.9). Equating these quantities, we find the amplitude of the magnetic field H of a classical electromagnetic wave, which corresponds to the sensitivity threshold of the eye. In order of magnitude, it is equal to

$$H = 2\ddot{y}\sqrt{\frac{2N}{\ddot{y}\ddot{y}}} \ddot{y} 4 \cdot 10\ddot{y}10 \text{ Gs}.$$

As can be seen from Figure 3.1, the EMF of this optical section of the spectrum at such low intensity is indeed the subject of quantum-

of your description.

Let us now find the equivalent amplitude of the optical radiation of a household light source, for example, an incandescent lamp with a power of 100 W. The optical part of the spectrum accounts for only

a few percent of the power, that is, about P ÿ 5 W. At a distance R ÿ 1 m, the optical radiation flux will be P/4ÿR2, whence

we obtain H ÿ 0.3 10ÿ2 G. As can be seen, there are much more grounds for considering such radiation as classical waves. It falls into the transition region between the classical and quantum descriptions. Indeed, optical radiation of such power exhibits

properties of both waves - interference phenomena, and quanta - photoelectric phenomena.

1.4.3 Electric field in the magnetoreceptor mechanism tions

The interaction of EMF with bound charged particles is,

obviously, a natural basis for the search for the primary mechanisms of magnetoreception. The action of fields on a quantum particle in some binding symmetric, for example, central, potential leads to

in the general case, to the splitting of its initially degenerate energy levels. It is therefore natural to compare the magnitudes of the splitting caused by magnetic and electric fields. This provides a criterion for the smallness of the electric field with respect to the atomic system in

magnetic field. It does not, of course, exhaust all possible situations, but nevertheless provides some estimates useful for magnetobiology.

For the purposes of our estimates, we assume that the particle is in some central potential. In a magnetic field H, the splitting of the levels (the Zeeman effect) of charge q and mass M is close to

$$E\ddot{y} \frac{q}{2Mc} H. \quad (1.6)$$

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In an electric field E the system acquires a dipole moment d ÿ
ÿE, ÿ is the polarizability. The energy of the moment ÿdE = ÿÿE2 depends on
square of the electric field. The perturbation operator in the field E is V = ÿdE
, where d = qr is the dipole moment operator of the ion.
Let's choose the z-axis in the E direction, then

$$V = \ddot{y}qrE = \ddot{y}qzE .$$

In the first order of perturbation theory, the energy shift of a non-degenerate level, for example, when H = 0, in a uniform field E is equal to (we follow designations [122])

$$E_n^{(1)} = V_{nn} = \ddot{y}_n|V|\ddot{y}_n = \ddot{y}qE\ddot{y}_n|r|\ddot{y}_n = 0,$$

where ÿn is the unperturbed wave function of the n-th level, n is the set of quantum numbers. The splitting of a degenerate level, in the absence of MP is determined by solving the secular equation

$$V_{nn} \ddot{y} E^{(1)}{}_n \ddot{y}_{nn} = 0 ,$$

where n and n refer to the states of the degenerate level, and they have the same parity. Thus, regardless of the MP correction
to energies depend on the matrix elements of the vector r or pseudo-
lar z between functions of the same parity.11 But such matrix
elements are equal to zero. Therefore, the splitting of the levels is determined by the second-order corrections (quadratic Stark effect)

$$E_n^{(2)} = \sum_m \frac{|(dE)_{nm}|^2}{\ddot{y}_n \ddot{y} \ddot{y}_m} = q^2E^2 \sum_m \frac{|(z)_{nm}|^2}{\ddot{y}_n \ddot{y} \ddot{y}_m} , m = n,$$

where the denominator is the difference in energies of unperturbed states.
The main contribution to $E_n^{(2)}$ create terms with the smallest values of the energy difference.
The states of the Zeeman multiplet in the central
potential have the same parity and corresponding matrix
elements are equal to zero. Therefore, the smallest values of the energy difference correspond to different values of radial or azimuthal quantum numbers. In order of magnitude, the splitting is equal to

$$E_n^{(2)} = q^2E^2 \frac{|(z)_{10}|^2}{\ddot{y}_{10}} .$$

11Excluding the cases of the Coulomb potential and the harmonic oscillator potential, when the steady-state functions may not have parity.

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Taking into account the scale of the transition energy ÿ10 ÿ 2/MR2, where R is the size the region of residence of the particle, and the approximate equality (z)nm ÿ R, we obtain the following relation for corrections to energies in electrical Czech field

$$E\ddot{y} \quad \frac{q2MR4}{2} E2 . \qquad (1.7)$$

The estimate gives, for example, the correct order of polarizability ÿ ÿ ÿ2E/ÿE2 ÿ q2MR4/2 of the ground state of the hydrogen atom.

By equating the splittings (1.6) and (1.7), we obtain an estimate of the quantity electric field, when the disturbances it introduces into an atomic-like system in a magnetic field become significant,

$$E\ddot{y} \quad \frac{}{MR2} \quad \frac{\overline{H}}{2cq} .$$

The following sections present numerous data indicating that biologically important ions: calcium, magnesium, etc., are the primary targets of magnetic field action on biological systems. Considering that the typical laboratory magnetic field level is approximately 0.5 Gs and substituting the orders of magnitude for the calcium ion
40Ca2+ in a capsule with an effective potential of radius 0.7 A $^{\circ}$, let's calculate E ÿ 10ÿ3 CGS units or ÿ 30V/m.

Biological tissue consists of 60–95% water. It has a relatively high dielectric constant for quasi-static electric fields ÿ ÿ 80. Therefore, when exposed to external

electric field, the change in the field acting on the ion in biological tissue is ÿ times smaller. Thus, the estimate

$$E\ddot{y} \ 100–1000 \ V/m$$

is acceptable for the highest permissible electric fields in the above sense. Note that the standard for residential
The level of the premises is 5–20 V/m with a frequency of 50 Hz. The assessment applies to the case of quasi-static fields, when the field frequency is much less than the scale of the transition frequencies ÿ /MR2 with a change in the radial quantum number. For the given system, this will amount to about 1010 Hz.

Note that we are talking about electric fields created by external sources. Electric fields induced by alternating current
MP, as noted above, are taken into account in the dynamic equation simultaneously with the MP through the vector potential.

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1.4.4 Limitations on plane waves

Until now, we have been considering mainly homogeneous magnetic fields and the electric fields they generate. That is, we have been talking about fields in the so-called near field, when the distance to the emitter is comparable to its dimensions. More precisely, if d is the emitter size and ÿ is the length of the EM waves, then the near zone occurs at a distance r to the emitter, approximately no more than

$$r0 \ \ddot{y} \quad \begin{matrix} d2/\ddot{y} \ d \ \ddot{y} \\ \ddot{y} \ d<\ddot{y} \end{matrix} \quad . \qquad (1.8)$$

In the case of a near field, the configuration of the EMF is determined mainly by the distribution of currents and charges on the emitter. If the distance r to the emitter is much greater than r0, the far-field approximation takes place. In this case, the EMF over a small interval, much less than r, is close to a plane wave (i.e., the wave amplitude changes little over this interval), and the field strengths are related by the relation

$$H = n \times E \quad ,$$

where n is a unit vector in the direction of wave propagation. From this, it is easy to find the energy flux density in a plane wave.

$$S = E \times H = 4\ddot{y} \ 4\ddot{y} \quad \frac{c}{} \quad \frac{c}{} H2n \ . \qquad (1.9)$$

For example, the conditions of the far zone are satisfied by EMFs falling to remote areas of the human body when using a cell phone. Remote zone conditions are specially organized during experiments with microwave radiation. In such cases the use of the idealization of plane waves is quite justified and convenient from a mathematical point of view.

Relations (1.6) and (1.7) that determine the order of splitting atomic levels in magnetic and electric fields, in the case of a flat EM waves provide estimates of radiation power levels when either electrical or magnetic effects are dominant.

Let us compose the ratio of quantities (1.6) and (1.7), taking into account that for a plane wave E = H,

$$\frac{Emag}{Eel} = \frac{3}{2M2R4cqH} \ .$$

Let us introduce the following convenient quantities

$$a = 2/MR2 \quad ,p \quad = mpc2 \ ,$$

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— the characteristic scale of the ion vibration energy in a cavity with an effective potential of radius R and the rest energy of the proton, respectively. Then the desired relationship takes on a convenient form

$$\frac{E_{mag}}{E_{el}} = \frac{a^2}{4q\,\pi N H},$$

where q = q/e is the relative charge of the ion. This relationship can be rewritten in an even more convenient form, taking into account definition (1.9):

$$\frac{E_{mag}}{E_{el}} = \sqrt{\frac{S_0}{S}}, S_0 = \frac{c}{\pi}\left(\frac{a^2}{8q\,\pi N}\right)^2. \qquad (1.10)$$

It is obvious that the value of S0 determines the threshold level of radiation power density at which magnetic and electrical effects are potentially equal. It is easy to obtain an estimate

$$S_0 \approx 8.8 \cdot 10^{-10}\ \text{W/cm}^2$$

for calcium in the binding cavity of calmodulin with a potential radius. This value, as follows from (1.9), corresponds to an amplitude $R \approx 0.7$ Å there magnetic component $H_0 \approx 2\sqrt{S_0}/c \approx 2 \cdot 10^{-6}$ G. In the diagram of Fig. 3.1, this level separates the lower region in the range of high frequencies, that is, in the sphere of action of the plane wave approximation, where the electrical component of the EMF can be neglected. As can be seen from the figure, the amplitude range of microwaves effective against E. coli, studied by Belyaev, Shcheglov, and others in [635], is almost lies entirely within the range of action of the magnetic component.

The power of microwave radiation, such as that from cell phones, decreases exponentially as it penetrates deep into biological tissue. Therefore, there is always a layer in which magnetic fields are more likely to occur. effects. In addition, the molecular mechanisms of the biological action of EMFs, discussed in the following chapters, show that the physical conditions for the realization of biological effects are simpler specifically for magnetic fields.

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Chapter 2

Review experimental results

The review includes only a small portion of published works on magnetobiology. Many remarkable experiments are not considered here due to the lack of a logical connection with the solution of the problem of the physical nature of magnetobiological effects, although they themselves These experiments are unique in themselves and represent significant scientific value. Such are, for example, epidemiological studies, which examine the relationship between the intensity of industrial frequency electromagnetic noise and the incidence of certain diseases. It is clear that there is a correlation between these factors.
does not mean that they are cause-and-effect dependent and is unlikely to help understand the nature of the effect. At the same time, these data are important socio-political factor.

The objectives of this book allow us to work only with ideas that are within the mainstream of traditional physics and raise virtually no doubt about their validity. Therefore, the criteria are clear
selection of experimental material. The selection was made based on the possibility of commentary from a physical point of view. The experimental data should contain dependencies, functions, and correlations that can be compared with various physical mechanisms likely underlying the observed effects. The subject of particular interest was

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whether experimental observations of polyextremal dependencies
MBE with a fairly complete description of magnetic conditions. Such observations are the most paradoxical and at the same time comparable with the mechanisms of non-thermal action of magnetic fields, in particular, with the ion mechanism interference that forms the core of the book. In most cases, not
The papers on the effect of variable magnetic fields were reviewed, in which the magnitude and direction of the constant magnetic field at the location of the experimental objects were not reported. The criterion of sufficiently complete information on the magnetic environment is beginning to be used by specialized journals when selecting materials submitted for publication.

The exposure time in the magnetic field is an important parameter on which the magnitude and sometimes the direction of the biological response depends. The study of the time dependences of the MBE constitutes the toolkit of almost half of the publications in the field of electromagnetic biology. These data are important for understanding the biochemistry and physiology of EMF reception by living systems. At the same time, the time dependences are, as a rule, relatively slow, with a characteristic time of 10
minutes or more, carry virtually no information about the primary physical process of converting the EMF signal into a biochemical response.
This book is primarily focused on the primary processes of magnetoreception. Therefore, numerous results of studies of temporary
dependencies remain beyond the scope of this review.

Let us just note that in most cases exposure times from several minutes to several months are used. Two types of dependences of the measured parameters on the exposure time are typical: an s-shaped curve with saturation and a bell-shaped dependence, for example [247, 416]. The first type is determined by the balance of the processes of accumulation and decay of the products of biochemical reactions accompanying the process of primary reception. The bell-shaped type of dependence reflects the additional inclusion of adaptive mechanisms that prevent the shift in homeostasis and ensure the stability of living systems in altered external conditions. Meanwhile, in

the body has a whole spectrum of simultaneously relevant temporary
scales of biochemical and physiological processes, including intrinsic biorhythms. Therefore, the measured time dependencies are often more complex than those indicated,
curves.

About 5–10% of magnetobiology studies report failures
attempts to observe MBE. These studies are also not included in the review, due to the impossibility of generalizing these data. Due to the large length and

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uncontrollability of the chain of processes of transformation of the MP signal into a measurable biological parameter, the absence of an effect in a specific experiment is normal in itself. Reproducible MBEs, as noted in [328, 562, 283, 644], can only be detected when both the "electromagnetic" and "physiological" windows are simultaneously hit. For example, Blank and Soo in [324] observed a change in the sign

effect of EMF on the activity of the Na,K-ATPase enzyme with varying initial enzyme activity. That is, in a certain range of initial activities, the effect of EMF was absent. This circumstance
practically did not depend on the parameters of the EMF, or even on the type of EMF stimulation, magnetic or electrical.

Temporal windows, time intervals when a biological system is able to exhibit sensitivity to magnetic fields, are also observed. Such windows have been found on different time scales, from minutes and hours [328] to seasonal variations [418, 644]. It is important to note that the reasons
insufficient reproducibility of magnetobiological experiments can be quite exotic. Thus, Simko, Kriehuber and Lange
[661] report that the biological reaction of human amnion cells arose or did not occur depending on which of the magnetic systems, Helmholtz rings or Merritt rings, was used

alternating magnetic field; the field amplitude was the same in both cases.
In experiments on the biological effects of microwaves, the result may be depend significantly on the distance to the emitter at the same energy flux density [138].

In most cases, experimenters needed a targeted search for relatively rare successful combinations of electromagnetic and physiological conditions. However, the effect of weak magnetic fields
The impact on biological systems manifests itself in a variety of experimental configurations. These are briefly listed below.

Some of the important experimental work is described or commented on in other sections of the book when comparing experimental and theoretical
Czech data.

Some undoubtedly important works, dating from the beginning of the century to the end of the seventies, are missing from the collections available to the author. libraries. However, there are reviews of such works [202, 710], which show the therapeutic use of magnetic fields, studies of physiological and tissue reactions to weak constant, variable, pulsed magnetic fields, magnetic vacuum and geomagnetic fluctuations. In fact,

the main “set” of magnetic configurations studied remained unchanged
exchangeable.

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It is interesting to point out some of the “pioneering” work on magnetic biology, published at the turn of the 20th century and earlier.1

- E. K. O'Jasti. Magic Magnet Mystery. "Hibernia", Dublin, 1798.
- W. Waldmann. Der Magnetismus in der Heilkunde. Dtsch. Arch. f. Geschichte der Med. und med. Geographie, 1:320, 1878.
- N.I. Grigoriev. Metalloscopy and metal therapy. St. Petersburg, 1881.
- V. Ya. Danilevsky. Research on the physiological action of electricity at a distance. Kharkov, Vol. 1–2, 1900–1901.
- B. Beer. Uber das Auftreten einer subjektiven Licht-emp findung im magnetischen Feld. Wiener clinic. Wochenschr., 4, 1901.
- C. Lilienfeld. Der Elektromagnetismus als Heilfaktor. Therapie d. Gegenwart, Sept., 390, 1902.
- P. Rodari. Die Physikalischen unf physiologisch-therapeutischen Einflus-se des magnetischen Feldes auf den menschlichen Organismus. Corre-spondenzblatt f. Schweiz. Arzte, 4:114, 1903.
- S. P. Thompson. A physiological effect of an alternating magnetic field. Royal Society, 82:396, 1910.
- G. Durville. Treatment of diseases with magnets. Kyiv, 1913, 74 p.
- C. E. Magnussen and H. C. Stevens. Visual sensations caused by a magnetic field. Philosophical Magazine, 28:188, 1914.

■ Many of the magnetobiology experiments have not yet been confirmed. research from other laboratories. Therefore, it would seem that there are no reliable facts for constructing theoretical models. However, the collected together, see, for example, [410], these experiments demonstrate a certain commonality in the manifestations of MBE under different conditions and at different biological objects. Only these common elements form the basis for subsequent theoretical generalization.

2.1 Brief summary of experimental work bot

The experimental works listed below are mainly those discussed later in the book. For convenience, the works are grouped

The author is grateful to Professor SN Uferom of the University of Leeds, thanks to whom it was possible to become acquainted with the rarity of O'Justy. Other publications are cited from bibliographies from [710] and [205].

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are determined by 1) the objects of study, 2) the parameters measured in the experiment, 3) the frequency ranges and 4) the configurations of the electromagnetic fields used to irradiate the organisms.

2.1.1 Research objects

The most common subjects and objects of research should be
carry

— biochemical reactions [370, 534, 180, 656, 142, 556, 325, 388]2
— processes of DNA restoration and destruction [399, 346]
— DNA-RNA synthesis [697, 391, 458, 547, 452, 531, 322]
— enzymes — membrane ion pumps [324]
— cells [670, 245, 663], amoeba cells [676], bacterial cells [579, 244], *E. coli* [229, 378, 246, 585], yeast cells [370],
Candida [579], plant cells [199, 80, 185], fungi [583], algae [334, 426], and insect cells [458]. Animal cells [391]: fibroblasts
[399, 642, 392, 503], mouse epidermis [717], erythrocytes [658, 578, 403], lymphocytes [228, 586, 687, 458, 335, 708, 729, 357, 485, 429], leukocytes [261, 431, 602, 669], osteoblasts [396], neoblasts [179, 129], endothelium [422], salivary glands [454, 456], thymocytes [709, 392], amnion [661], bone cells [440]. Tumor cells [601, 434, 335], Ehrlich carcinoma [398, 140], breast cancer MCF-7 [469, 318], pheochromocytoma [316], human leukemia U937 [248, 398, 338], E6.1 [363], embryonal carcinoma F9 mice [402], C6 gliomas [250], human osteosarcomas TE-85 [350]
— brain tissue [266, 482, 572, 484, 480, 132, 1, 472, 515], nerve [657], intestines [526], bones [628]
— organs: brain [203, 636], heart [106],
— physiological systems: central nervous system [268, 203, 521], neuroendocrine [630], immune [687]
— organisms: plants [605, 501, 502, 54, 173, 667] and plant seeds [643, 644], buds [418], insects [328], rats [347, 593, 696,
175, 188, 158, 626, 500, 79, 181] and rat embryos [420, 561], mice [261, 504, 505, 602], newts [251], worms [491, 179, 129], doves [175], chickens [646], snails [546, 615], human body [225, 650]
— ecosystems and biogeocenoses [700, 595, 470, 698, 550, 275]
— amino acid solutions, — although they are not a biological object, but demonstrate MP effects that are essentially very close to those discussed — [144, 142, 143].

[2] Data are scarce. The effect of low-frequency magnetic fields on biochemical reactions *in vitro* remains a poorly understood issue.

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2.1.2 Measured parameters

The measured parameters were:
- physical: dimensions and weight of the object [646, 501, 502, 173, 667], viscosity cell suspensions [246, 245], rheological properties of cells [403], number of cells [583, 602, 429, 244, 717, 338, 676] and subcellular structures [661], surface electric charge [248, 140], transmembrane potential [526], structure of images of electron and other microscopies [454, 185, 316, 472], current strength in an electrochemical cell with an object [144, 142, 143], luminescence of photoprotein [663], intensity of radiation of a radioactive label [697, 440, 656, 350, 556, 503], DNA mobility [516], analysis parameters: chromatographic [144, 142], fluorescence [440, 503] and microfluorescence [708, 709, 485, 140, 628], spectrophotometric [325, 388], gel electrophoresis [456, 531], radiographic [454, 578, 458], ECG, EEG, ECoG [205, 158, 650]
— biochemical: activity or level of the enzyme during transcription of the ÿ-galactosidase gene [229], adenylate cyclase [396], lysozyme [370], protein kinase [247], Na,K-ATPase [658, 323, 324], acetylcholinesterase [373], enolase [378, 585], melatonin [347, 430, 630, 397, 626, 405, 569, 626, 500], norepinephrine and adrenaline [188], phosphorylation of myosin light chains [656], choline [515], ornithine decarboxylase [534, 641], cytochrome oxidase [325], N-acetyl-serotonin transferase [548]. Calcium efflux [268, 572, 334, 484, 480, 653, 315, 238, 373], intracellular and extracellular concentration ions [524, 363], the concentration of lipid peroxidation products and total thiol groups [132], uptake of radioactive tracers [658, 391, 335, 199, 398], ribonucleic acid (mRNA) level [431, 80]
— biological: impulse activity of neurons [657, 1], stability of biological rhythm [106], parameters of morphogenesis and development [251, 328, 418, 644], seed germination rate [643], motility and cell morphology [334, 670, 426], cell proliferation [402, 399, 642, 199, 250, 179, 140, 469, 503, 318]. Gene expression [456, 547]. Behavior of individuals and groups: conditioned reflex activity [203, 593, 696, 175], reaction time [505, 615] and regeneration [491], motor and research activity [79, 181], memory [636]. Physiological sleep parameters [225].

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2.1.3 Ranges of electromagnetic fields

The behavior of biological systems in electromagnetic fields of various ranges is observed: — constant fields, [261, 624, 401, 548, 598, 501, 502, 657, 542, 328, 418, 655, 181, 403, 472, 676, 556] — geomagnetic fields [728, 532, 319, 327, 558, 498, 591, 554, 559, 622, 289, 592, 341] — range < 1 Hz, [505, 657, 140] — range 1–100 Hz, [420, 454, 402, 399, 646, 391, 334, 687, 440, 106, 642, 434, 335, 426, 1, 132, 175, 630, 188, 709, 357, 316, 246, 626, 144, 142, 378, 350, 491, 485, 615, 667, 670, 429, 324, 500, 143, 245, 585, 717, 225, 469, 628, 641, 503, 643, 644, 650, 661, 363, 515, 388, 318] — range 102–103 Hz, [646, 484, 480, 323, 526, 79, 325] — 1–103 kHz range, [658, 697, 323, 250, 179, 325, 669] — 1–100 MHz range, [587, 244] — 102–103 MHz range, [268, 247, 572, 583, 378] — more than 1 GHz, [169, 713, 220, 12, 464, 572, 8, 587, 91, 568, 463, 428, 206, 168, 635] — narrowband noise and wideband MP [248, 158, 250, 531, 641, 140].

2.1.4 Field configurations

Various combinations and orientations of fields are used: — parallel constant and alternating magnetic fields [696, 334, 332, 526, 426, 615, 667, 429, 179, 129, 79, 628, 388] — perpendicular constant and alternating magnetic fields [696, 480, 602, 387, 644] — inclined fields [642, 106, 335, 316, 246, 350, 485, 245, 387, 717, 641, 140, 643, 363] — rotating magnetic fields [593, 504, 505, 626, 650] — close to zero magnetic fields [271, 272, 467, 330, 532, 351, 83, 273, 61, 201, 718, 383, 154, 174, 182, 341, 502, 251, 105, 338] — electric fields, also in combination with MF [347, 370, 658, 399, 601, 484, 687, 440, 480, 323, 585, 475, 652, 668, 669] — parallel MF and perpendicular electric field [144, 142, 143] — pulses and pulse trains of MF of various shapes [229, 454, 578, 391, 456, 657, 542, 248, 709, 250, 158, 636] - with low-frequency modulation of EMF [268, 531, 641]

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— movement of biosystems in a changed MP [173, 181]
— low-frequency MF of ultra-low intensity < 1 ÿT [420, 391,
369, 397, 250, 626, 405, 550, 324, 143, 636, 717, 225, 390, 469]
— MM radiation of ultra-low intensity [587, 463, 635, 138, 120].

Unfortunately, a number of interesting works are difficult to classify as any of the listed combinations, since, and most often, The level of constant magnetic field at the experimental site is not reported. This parameter is often as important as frequency and amplitude. alternating field.

The works cited here are provided as separate references only. examples illustrating the diversity, completeness, and commonality of magnetobiological effects. Even based on this multiplicity of manifestations, it must be recognized that the biological action of electromagnetic fields is not an exotic, highly specialized effect, but a general phenomenon, a subtle regulatory mechanism, possibly used by nature on global, planetary, and temporal scales. All However, not everyone shares this point of view [398, 677]. In the latter The work concludes that the general cellular effect of low-frequency magnetic fields probably does not exist. The basis for this conclusion was the low reproducibility, excluding experiments with melatonin (see Reiter's review [631]), of the results of experiments repeated in different laboratories. However, the validity of the use of statistical methods in this The situation is debatable. One could equally well consider all of science as non-existent, since only a small proportion of people are involved in scientific activity. Low reproducibility of results in different groups with high, often more than ten-year, reproducibility in each of the groups, indicates low reproducibility *conditions* for conducting experiments.

Information about the possible physical nature of the observed magnetobiological effects is contained mainly in the “physical part” of the experiments, that is, in the parameters of the effective magnetic fields. Therefore, the main attention is paid to the details of the MP configuration, which were decisive for the success of one or another experiment. "Biological part", the preparation of biological systems that provide their preparations, proper living conditions, as well as the measurement procedure of the final parameter—often very complex and skillful experimental techniques—remains beyond the scope of discussion. The choice of the low-frequency range of the magnetic field is dictated, as already mentioned, by the possibility of neglecting the induced electric field, which directly proportional to the frequency, and, mainly, to the fact that it is in this

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the paradoxical nature of biological phenomena is most clearly manifested in this range EMF effects. The use of constant magnetic fields and combined constant and low-frequency fields is discussed in more detail below.

When describing the experiments we will use a single scheme description or formula of the experiment. It will indicate the controlled parameters of the MP, the intervals of their change and some statistical data. The units of measurement correspond to frequently used in experiments of this kind: for the induction of magnetic field B — ÿT or ÿT, for frequencies f — Hz or Hz, for times T,ÿ — s. For example, the formula

B(45 ± 5)b(0–12/1)f(50, 60)Bp(!)n(5–8)g(?) (2.1)

means that the constant MP B (will also be denoted as BDC or HDC (depending on the context) is equal to 45 ÿT with an accuracy of 5 ÿT, parallel to it the alternating field with *amplitude,* i.e. peak value, b (or BAC) varied from 0 to 12 ÿT with a step of 1 ÿT. In different series of the experiment, two fixed frequencies were used, either 50 Hz or 60 Hz, the magnitude of the perpendicular component of the constant MF Bp is not was controlled (!), the number of repetitions n (experimental points) for each set of MP parameters was from 5 to 8, the MP gradient unknown (?). For pulsed MP, b denotes the pulse height. The order of specifying the parameters is arbitrary.

2.2 Biological effects of constant magnetic fields

The influence of constant magnetic fields on living systems is discussed comparatively long ago. The biological effect of constant magnetic fields, unlike low-frequency ones, is not seems paradoxical at first glance, since there are no quanta of electromagnetic fields, the energy of which could be compared with the energy biochemical transformations. It seems plausible that the action constant MP proceeds by a different mechanism and is capable of accumulating on at some biological level, bypassing the stage of primary physical oscillators. However, even in this case, there are no reliably established mechanisms for the primary reception of weak fields, with the exception of those associated with so-called biogenic magnetite, no [662].

Malko, Konstantinidis et al. [655] believe it is generally accepted that constant magnetic fields do not have significant adverse biological effects, which is confirmed by long-term practice of magnetic resonance imaging [598]. They studied the reproduction

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yeast cells *Saccharomyces cerevisiae* under conditions of a static magnetic field of 1.5 T created by a clinical NMR scanner. Experimental and control cells were propagated in food broth in for 15 hours, which corresponded to seven cycles of cell division. The surrounding constant and alternating, 60 Hz fields did not exceed 50 and 3 ÿT (eff.), respectively. Data processing showed the absence of statistically significant effect.

The authors suggested that this MP would not affect cells. mammals, since most of the chemical reactions for these cells and for single-celled organisms are identical. They question the results of studies that found an adverse effect of constant magnetic field on the blood of mice [261], on Drosophila eggs [624] and trout caviar [401]. However, it is difficult to agree with this conclusion, in view of the sufficient amount of data accumulated to date on the biological effectiveness of both strong and weak static MPs, including changes in enzyme activity [603, 468, 588].

A continuously applied field of 20 mT caused in [472] a 25% change in the histological parameters of the cerebellar tissue of chickens. Fields of the order of 71 mT and 107 mT, studied in [676], caused a growth retardation amoebae populations from 9 to 72%. In [579], growth stimulation was observed with 15 mT and inhibition at 30–60 mT in various bacteria and fungi. Furthermore, from the perspective of the most probable interference mechanisms of MBE, strong magnetic fields in certain cases are less effective than weak fields comparable to the geomagnetic field.

Excluding experiments using relatively strong magnetic fields, more than 1 mT, the question of possible adverse consequences of staying in magnetic fields other than geomagnetic ones has also not been resolved. The importance The answer to this question is that the level of permanent MF of man-made origin and its gradient vary greatly from place to place. In the same production area, a permanent MP can amount to both percentages of the geomagnetic field level and tens oersted near massive iron structures and take these extreme values at distances of the order of meters. The impact of constant magnetic fields on human health and international programs in This area was discussed by Ripacioli and Greenbaum in a review article [634].

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2.2.1 Biological effects of weak magnetic fields lei

In [523], Lecht investigated the processes of dispersion of melanophore pigments in samples from tadpole skin under the influence of a stimulating hormone and their aggregation under the influence of light. It turned out that
These processes proceed at different rates depending on the magnitude of the constant magnetic field. Doubling the field, from 42 to 84 ÿT, led to a decrease
the rate of dispersion by 22–24%. In these experiments, the MBE was practically independent of either the hormone concentration or the degree of illumination, which, according to in the author's opinion, indicates modulation of the secondary magnetic field signaling processes involving calcium.

The effect of 15 min exposure of *E. coli* cells to a magnetic field altered compared to the geomagnetic field on the viscosity of the cell suspension was studied by Belyaev, Matronchik, and Alipov in [277, 136]. The range of magnetic field variation was 0–110 ÿT. The absolute maximum of the MBE was
about 25 ± 2% in near-zero MP. The dependence of the MBE on HDC showed a polyextreme character with alternating signs of the effect
in a successive series of extremes, Fig. 4.48.

Markov, Mukhsam, and Pilla found in [556] that the rate of Ca2+ -dependent calmodulin phosphorylation of myosin light chains in a cell-free reaction mixture was strongly dependent on the level of constant magnetic field. The monotonic increase in rate, determined from 32P radiolabel counts, ranged from 80 to 280% with varying magnetic field.

from 0 ± 0.1 to 200 µT.

2.2.2 Orientation in the Earth's magnetic field

The effects of orientation of living organisms in conditions of a weak magnetic field, in particular, a geomagnetic field, deserve special attention.
(GMP). Many biological systems have been found to be capable of both
would be able to “see” magnetic field lines and orient themselves in relation to them [28, 269]. Thus, biosystems can respond not
not only on the magnitude of the magnetic field, but also on the change in its direction. However, In this case, magnetosensitivity does not constitute an obvious paradox. Kirschvink, Jones, and McFadden in their book [28] provide more or less satisfactory considerations about the nature of this phenomenon. The journals *Nature* and *Science* publish articles on this issue with surprising consistency, while the general physical issues of the paradoxical biological action of EMFs have received virtually no positive coverage.

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Some exhibit orientation ability in weak MP
bacteria [319, 554], birds [728, 327, 289, 603, 269], fish [498, 622, 341], insects [532, 558, 591], mammals [559, 735].

For large-scale orientation using a compass, it is necessary to link the magnetic map to the geographic map. For a person, such
The reference is the knowledge that the magnetic meridian approximately coincides with the geographic one. Birds do not possess such knowledge, they are forced to adapt or learn by coordinating their magnetic "sense" with their innate navigational aids, such as
using the polarization distribution of daylight. After the training period, they do not need daylight and some birds are capable
to make seasonal migrations at night. Able and Able [230] placed sparrows were kept for four days in open cages in a local magnetic field, rotated by 90 degrees relative to the natural geomagnetic field.
After this, the preferred direction of night flight also changed by 90 degrees in both young and mature individuals.

In [349] Collett and Baron found that bees remember and then recognize a visual picture of a particular location based on
the lines of force of the geomagnetic field, that is, using them as a system
reference. This makes it much easier to store and retrieve information.
tions from memory.

Newts also have compass magnetic orientation under visible light conditions, but not in the dark. The nature of orientation
changes depending on the spectral composition of light. It is therefore believed that the photoreceptors of the retina may be suitable targets for exposure to constant magnetic fields, since their orientation is associated with body position. At the same time, as Lochman [537] showed, there is
and light-independent magnetic compass orientation in some invertebrates, fish and mammals.

Semm and Beeson [657] examined the optic nerve and trigeminal
The bobolink ganglion was studied with short-term variations in a local constant magnetic field. They wanted to identify field-sensitive nerve fibers and determine whether their sensitivity was sufficient to implement a "magnetic map." Spontaneous activity of certain nerve regions or cells (182 cells in 23 birds were studied) was recorded using micropipette electrodes with a diameter of 1–5 ÿm. A tiltable pair of Helmholtz coils was used.

Only a portion, 14%, of the cells with spontaneous activity turned out to be sensitive to variations in MP. These cells did not respond to vibration and mechanical stimulation of the bird's body. The nature of the response was

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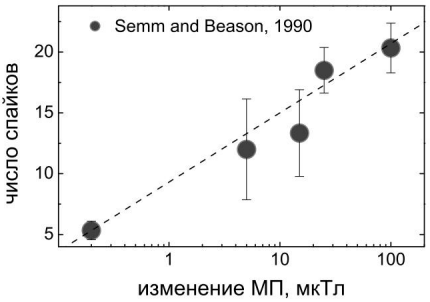


Fig. 2.1: A change in the vertical component of the local MP for 0.2 s causes an increase in spike activity trigeminal ganglion cells, according to [657].

different in different cells. Some cells responded only to an increase, others to a decrease in MP. Some cells were sensitive to ultra-weak, ÿ 200 nT, variations included in the interval from 0.2 up to 4 s, pulse front 6 ms. Dependence of the number of activity spikes on The magnitude of the stimulus for one of the cells is shown in Fig. 2.1. The logarithmic dependence of sensitivity to a stimulus is characteristic of biological systems. This indicates that this dependence reflects secondary biochemical processes, and not the primary biophysical reception of the MP. This is also indicated by the relatively long recovery time, 10–20 s, of the initial activity of the cell after removal

weak magnetic stimulus. The authors believe that the "magnetic map" birds responding to variations of the order of 100 nT [603] could be is caused by the magnetic sensitivity of neurons.

2.2.3 Effects of a magnetic field close to zero

It has long been noted that changes in the level of constant MP are not indifferent for living organisms. Life on Earth has always existed in conditions of a geomagnetic field, albeit weak by everyday standards, but different from zero. It is widely believed that biological systems many millennia have somehow adjusted to the natural level of the magnetic field. Therefore, a change in the level of the magnetic field can lead to various pathologies. Some researchers believe that the inversion of the poles of the Earth's magnetic dipole could cause biological effects on a planetary scale [700, 595, 470, 698, 275].
In particular, a correlation between the emergence and disappearance was discovered biological species with an average frequency of GMF inversions, Fig. 2.2.

As is known, a change in the orientation of the Earth's magnetic field occurs approximately once every 200 thousand years (varies from 10 to 730 thousand years) and continues for about 4–5 thousand years, while living organisms are

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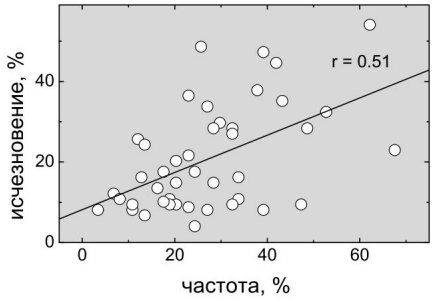


Fig. 2.2: Correlation diagram: on the X-axis is the index of the frequency of GMF inversions, on the Y-axis is the index of the disappearance of biological species. Data processing Fig. 24 from [377].

are called for a long time in changed magnetic conditions, in particular, in under conditions of significantly, up to 10%, reduced geomagnetic field, see, for example, Skiles' review in [28]. Skiles argues that in At present, the process of GMF inversion is taking place. Since during inversion geomagnetic field is different from the dipole field, local magnetic conditions include even closer to zero values [594].

Libow [525] believes that disturbances of biological species in a changing geomagnetic field are more likely associated with cyclotron conditions resonance of some ions in the GMF and in the endogenous electric field organisms. Unfortunately, this hypothesis, in contrast to the already established fact of biological activity of the zero field, is difficult check. Moreover, the very idea of cyclotron resonance in biology has not yet received physical justification.

The relative simplicity of implementing the conditions of MP, close to zero, The presence of such conditions in the professional activities of certain categories of workers and employees, in particular cosmonauts and submarine personnel, led to scientific research into the biological effects of magnetic vacuum or zero magnetic field. A review of such work up to 1976 is available in the monograph by Dubrov [377] and up to 1985 in the monograph by Kopanev and Shakula [117]. It is usually possible to reduce the magnitude MP in the experimental volume is two to three orders of magnitude higher than GMP. There are also sophisticated magnetic vacuum systems with passive and active compensation, in which the field is reduced by 105–106 times [54], and more [37].

Plants exhibit biological effects of magnetic vacuum [83, 383, 174, 502, 54, 199, 80, 185, 105], microorganisms [154, 182], insects [271, 532], worms [129], newts [251], fish [61, 201, 341], mammals [467, 330, 351, 273], various cells [275], organism human [272, 273, 718].

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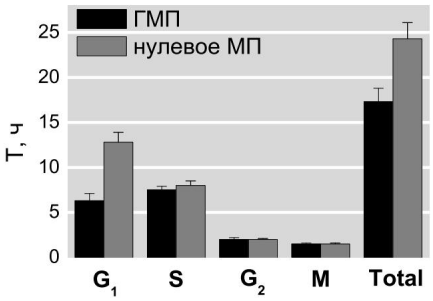


Fig. 2.3: Effect of MP on phases reproduction cycle of pea root meristem cells. G1 phase — RNA and protein synthesis, S - synthesis DNA, G2 - post-synthesis, M - phase of mitosis, Total - entire cycle, according to data from [199].

No response of plants to zero MP could be detected in [380]. [219] observed a difference in the responses of the right and left isomeric forms onion seeds.

Root hair growth on carrot and belladonna induced by some genetic methods, were studied in a magnetic vacuum of ÿ 5 nT by Kato, Kamada and Asashima [502]. Compared to the control, in a field (50 ÿT), root growth on belladonna was accelerated by 40–56%. The root temporization of carrots remained almost unchanged. At the same time, a strong constant field of ÿ 0.5 T compared to the control of ÿ 10ÿ3 T caused ÿ 25% acceleration of root growth in both plants. It was shown that the modified constant magnetic field acts in these experiments specifically on plant roots, since preliminary treatment environment in which the plants grew, under similar magnetic conditions did not lead to any changes. It was concluded that strong MP and magnetic vacuum may have different targets in plants, then There are different mechanisms of biological action. The authors also cite a study where similar conditions, HDC ÿ 5 nT, caused death. newt embryos in a few days.

Long-term exposure of oat plants in the early stages of ontogenesis to hypomagnetic conditions, with compensation of the GMF up to 1% of its local magnitude, caused stimulation of plant growth [105].

Bacterial cultures respond to screening from GMOs extremely diverse, with changes at the phenotype and genotype levels, which is manifested in both metabolic and physiological processes [377]. Hypomagnetic conditions, up to 0.1 ÿT, led to an increase in the size of cell nuclei and a significant decrease in the intensity of mitoses *in vitro* in mouse and hamster cells [187]. At the same time, hypomagnetic conditions in [460] did not lead to a noticeable change

processes in isolated cells of some mammals.

Often shielding from GMF was carried out using protective

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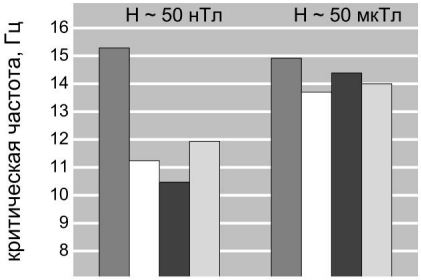


Fig. 2.4: Response of one of the human rhythms to zero MP for 4 subjects. Averaging - on the left for the days of exposure, on the right 3 days before and 3 days after it. data [272].

metal boxes made of soft magnetic materials. Such shielding always leaves the question of whether the observed effect could have been is caused by the changed level of variable magnetic fields and electrical fields. Therefore, a comparison was made with a control group of biological objects located in metal non-magnetic containers [467, 330, 54, 199, 80, 185].

In a series of works [54, 199, 80, 185] Govorun, Danilov, Fomicheva and Belyavskaya investigated the life processes of germinating seeds of pea, lentil and flax plants. A magnetic vacuum was created due to shielding by a multilayer permalloy screen box up to level of 10ÿ5–10ÿ6 GMP. It was shown that the dominant reaction The effect of magnetic vacuum is to reduce the rate of seed germination by 30–50% [54]. The proliferative pool of root meristem cells decreased from 90–96% to 68–75% with reliable statistics [199], data on changes in the duration of different phases of the cell reproduction cycle are shown in Fig. 2.3. The isotope hydrogen 3H was used as a radioactive label . The authors suggested that the response reactions at zero MP in these plants are associated with the processes of RNA synthesis and proteins, rather than with DNA synthesis or mitosis. In [80], the dynamics of RNA synthesis and some proteins in meristem cells was studied using fluorescence spectroscopy methods, and individual features of transcription processes in plant cells of different species were shown. Electron microscopy of root meristem cell sections revealed structural and functional changes in the state of the cells, primarily Ca-homeostasis [185]. Under conditions of zero MP, free and weakly bound calcium appeared in the hyaloplasm of cells, which was absent under growth conditions in GMF.

Also, many experiments [271, 272, 532, 351, 83, 61, 201], among which the relatively recent work of Kashulin and Pershakov [105], were carried out under conditions of compensation of the GMP using artificial

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magnetic field sources such as Helmholtz coils. Beischer in [272] used an 8-meter coil system for four subjects simultaneously. Figure 2.4 shows the response measured under these conditions.
functional characteristics of the human central nervous system after a 10-day stay in a magnetic vacuum. It is clearly visible,
that for three out of four subjects the average heart rate was significantly is decreasing.

Unfortunately, with very few exceptions, published works on the biological effects of zero MP do not contain any dependencies
effect on the field strength. Such dependencies are of interest,
because they carry information about the primary processes of magnetoreception.

Asashima, Shimada and Pfeiffer [251] exposed Japanese larvae to newt in the developmental stage of 5-day exposure in a magnetic vacuum 5 nT. On the 20th day of development, this led to distorted formation of the spine, abnormal development of the eyes, and general slowdown
development and even to the emergence of two-headed individuals. Exposure effect vacuum was found to be effective in the early stages of larval development, including the gastrula stage, and was 100–200%.

Belyaev, Alipov and Harms-Rindal in [275] measured the dependence of the anomalous viscosity of a suspension of *E. coli* cells after 15 min of exposure to altered, compared to the geomagnetic, magnetic field. When moving from the field exposure of 2 ÿT to 0 ± 0.1 ÿT, a 5% increase in MBE was observed. Similar effects under these conditions were also found in other cells,
rat thymocytes and human fibroblasts.

In [129] Lednev, Srebnitskaya et al. observed the zero-MF effect in the process of mitosis of neoblast cells of regenerating planarians. The constant field was varied from 200 to 0 ÿT with an accuracy of 0.06 ÿT. There appeared an increase in the mitotic index by 37 ± 12% when moving from a field value of 0.2 ÿT to a zero value, Fig. 4.47.

Not all biological systems measured in certain parameters show the effectiveness of magnetic vacuum conditions. In [338]
studied the proliferation of leukemia cells in a residual field of 20 nT after magnetic shielding. Although some statistically
A significant difference with the control, outside the shielding chamber, was recorded, the effect was quite small, < 5%.

It should be noted that the biological effects of magnetic vacuum are indirect evidence of the quantum nature of the MBE. From the point of view of classical dynamics of relatively free charges, for example,
ions in the solution, the decrease in the magnetic field is not accompanied by any qualitative changes. Neither the geomagnetic field, nor, especially, much

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smaller fields have virtually no effect on the particle's trajectory in the mean free path interval. Thus, the relative deviation of an ion with a charge
q with mass M in MP H ÿ Hgeo during the free path at room temperature, t ÿ 10ÿ11 s, will be ÿct ÿ 10ÿ9, where ÿc = qH/M c
— the cyclotron frequency of the ion. Bound particles, ions and electrons, oscillating in the magnetic field experience the so-called Zeeman splitting energy levels is a quantum phenomenon, given the microscopic scale of the oscillations. In the absence of a magnetic field, the splitting also disappears, and the levels become degenerate. It is unimportant that the magnitude of the splitting was of the same order of smallness, ÿ 10ÿ9 in comparison with ÿT . It is important that the symmetry of the particle's wave function changes, and this There is a qualitative change. No other qualitative changes accompanying the deprivation of the magnetic field are observed, which is an indirect indication of the quantum nature of the MBE.

2.2.4 Biological effects of gradient magnetic fields

Over the past decade, several companies have been producing a variety of magnetic bracelets, necklaces, patches, etc. These devices are generally in demand, but lack the necessary scientific research. Since magnetic field sources in this case are localized away from biological receptors, it cannot be ruled out that the possible effect of such devices is due to the spatial heterogeneity of magnetic fields. Various magnetic therapy devices and popular publications on this topic are available online; see, for example,

.

In medical practice, so-called magnetophores are also used [197]. They are flexible rubber pads of several thicknesses
millimeters, which are cut to the required size from a roll. The rubber includes a magnetically hard filler, magnetized in a specific pattern with alternating magnetic poles on the surface.

sheet. Such a source of MP provides strong heterogeneity of MP near the surface.

There are very few scientific studies on the biological effects of such devices.

On the therapeutic effect of magnetophores, acceleration of reparation tissue after skin plastic surgery is reported by Usacheva in her monograph [194]. These data are confirmed in the work of Shilov, Rabinov-

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cha and Kuznetsova [214], where they studied the influence of a magnetophore applicator on the intensity of lipid peroxidation processes in human skin. Induction and gradient of magnetic fields on the surface of the applicator were 30 mT and 5 mT/mm, respectively. The intensity of oxidation was measured using the ultraweak chemiluminescence characteristics of skin homogenates. The use of a magnetic field of the specified configuration completely removed the 20% effect of free radical activation.
lipid oxidation due to hypoxia.

Clinical data from Lin, Singleton, et al. [445] indicate that Permanent magnet matrices with a strength of 3000 Gs have some neurological effect on people, but do not relieve inflammation or reduce pain.

In the work [514] Krylov and Tarakanova report the discovery of different biological effects of two poles of permanent magnets, the magnetic field of the south pole had a stimulating effect on growth plants. In [365] Davis and Rawls showed that plants grew faster in magnetic north pole field. Similar data were confirmed by Ruzik, German et al. in [704], here the south pole proved to be the stimulating factor.

Kogan and Tikhonova [113] studied the movement of the ciliate *Paramecium caudatum* in a capillary with a diameter of 0.5 mm and a length of 50–70 mm containing a nutrient solution. The movement of the paramecium was quite regular. The ciliate periodically moved from one end capillary to another, with the average residence time in any half of the capillary lasted from 17 to 50 seconds, depending on the individual characteristics of the animal. Then the capillary was brought to one of the poles of a permanent magnet with a strength of 160 Oe or, in another experiment, about 700 CE. It turned out that paramecia were good at distinguishing between the poles. They lingered for long periods at the south pole and avoided the north pole, as if they carried a Dirac monopole. The asymmetry reached 300% and was generally proportional to the strength of the magnet.

Kavopol, Wemil et al. [567] observed the response of sensory neurons in cell culture to a magnetic field gradient. In in such a MP the probability of “firing” the action potential changed neuron. A gradient of 1 mT/mm blocked 70% of the AP (action potential), 1.5 mT/mm - 80%. At the same time, a constant field of 0.2 mT with a gradient of 0.02 mT/mm did not cause any changes.

It should be noted that the physical mechanism of detection is unclear. direction of the MP by biological systems. For this, another reference vector is needed, in relation to which discrimination of the direction of the MP could be carried out. One of such vectors is

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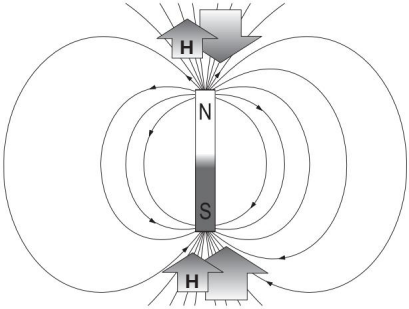


Fig. 2.5: Magnetic forces
permanent magnet lines and
carrier directions of MP and
magnetic field gradients near the poles
magnet.

gradient of the absolute value of the MP, Fig. 2.5. As can be seen from the figure, the MP and its gradient are directed in the same direction near the south pole of the magnet and in opposite directions near the north pole.
There are currently no data on similar effects for cell cultures in which the cells are randomly oriented. For plants, the vector that orients the cells and therefore can serve as a reference in the process of detecting the direction of the magnetic field is the gravity vector. It should be noted that the above experiments claimed

different actions of the magnet's poles. This would be the case if the authors showed that the magnetic field of a given direction and magnitude, created in two different ways, say, the location of the north pole
a bar magnet to the right of a symmetrical object, or a south pole to the left, would produce different biological effects.

It is interesting that in the work [483] Yano et al. describe exactly this experiment. Test tubes with radish sprouts in gel were placed
on the platform horizontally. Slow rotation of the platform around
the horizontal axis excluded the directed action of gravity on
sprouts. Illumination of the test tubes along their axes set the direction
root growth. On each of the test tubes, a permanent magnet in the form of a disk, magnetized along the axial direction, was attached in the middle on the side
axis. Some magnets were oriented with their north pole toward the axis of the test tube, part on the contrary. Brass disks of that
the same shape and size. In such a device, the plant root grew under conditions of a constant magnetic field gradient, always oriented towards the magnet,
and also in a constant magnetic field, the direction of which depended on the orientation of the magnet. It turned out that magnetotropism depends on the orientation
magnet. The root sprouts deviated more towards the magnet,
if the latter was facing the plant with its south pole. The approximate average values for deviation per day are as follows: control -
-0.01 ± 0.09 mm, north pole - 0.05 ± 0.08 mm, south pole -

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0.14±0.1 mm. In the center of the test tube, at the intersection of its axis with the axis of the magnet, The magnetic field was approximately 40 mT with a gradient of 10 mT/mm. This experiment demonstrates that it makes sense to talk about the biological system detecting the magnetic field direction relative to its gradient.

In a series of works [623, 389] Rai, Singh et al. observed a different the action of the fields created by the north and south poles of the constants magnets on water samples. The water condition was tested according to various biological reactions. However, in this case, reliable There were no conclusions, since the experiments were conducted for other purposes.

As discussed further in the book, the biological effects of low-frequency magnetic fields and microwaves have certain similarities and, probably, in some cases, also a common nature of the physical processes underlying such effects. Therefore, it is interesting to point out work [138] by Gapeev, Safronova et al., in which they investigated the frequency spectra of the effect of microwave radiation on immune cells mouse systems. Near- and far-field radiation modes were used. zones, see section 1.4.4, which provided equal flux densities radiation energy on the samples. It turned out that near-field radiation had a pronounced resonance-like effect on the cells, that is, there was a maximum in the spectrum. At the same time, far-field radiation had only a frequency-independent effect. Note that for far-field radiation has relatively small field gradients: the plane-wave approximation is often sufficient. At the same time, in the near zone, actually close to the emitter, the field gradients are ki.

We also note the work of Makarevich [130], which studied the influence magnetoplasts - ferrite-filled magnetized polymer composites — on the growth processes of microorganisms. The residual induction on the surface of the magnetoplast samples was 0.1–1 mT. Microbial strains were incubated in Petri dishes, where cylindrical magnetoplast samples were also placed. After two days of incubation, ring-shaped areas of accelerated and retarded growth were observed around the magnetoplast samples, depending on the magnetization of the samples. In some experiments, accelerated growth occurred.

near the north pole of the magnetoplast, magnetized along the axial axis. Conversely, near the south pole, microbial growth was slow. The possible role of magnetic field gradients was not discussed in this study.

Special studies on the separation of the effects of homogeneous and gradient MP are not known. Also, possible physical mechanisms of biological reception of direction have not been discussed in the literature.

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MP relative to its gradient, that is, the mechanisms of biological
sensitivity to the sign of the scalar product B ÿB.

2.3 Biological effects of variables magnetic fields

The biological effects of alternating magnetic fields have been studied for a long time
without taking into account the level of constant magnetic field at the place of the
experiment. It was assumed that the amplitude and frequency of the alternating
magnetic field, or the shape and periodicity of the pulses during pulsed exposure, themselves
sufficient for a complete characterization of magnetic conditions. The study of
amplitude dependencies, in turn, was restrained
intuitive understanding of the resonant mechanism of MP reception
biological objects, when the main parameter is the field frequency, although
amplitude-frequency windows in the biological effects of EMF were observed by
Bowen, Kaczmarek, and Adie [268, 266] and Blackman, Elder, and others [482] already in
seventies. Plekhanov [162], summarizing the long-term experimental results of the
Tomsk group of magnetobiologists, also records the existence of windows of MF
efficiency.

This section mainly considers those experiments that reveal complex frequency and
amplitude spectra.
MBE [220]. It is the spectral curves that are most informative with
from the point of view of the physics of primary processes of magnetoreception.

2.3.1 Effects of magnetic field modulated by size

In a series of fundamental works by Blackman et al. and Libow et al. in the eighties,
it was established that the level of constant MF determines the position of the maxima
of the frequency spectra of the MBE in some
biological systems [638, 524, 564, 527, 332]. The importance of taking into account
the constant geomagnetic field in experiments with biosystems in EMF
noted by Kremer, Krause, et al. in [548], Blackman, Benan, et al. in
[638] The dependence of the effects of alternating magnetic field on the magnitude of
the constant component is indicated by Lednev [519], Liskov, Chernyshev, and others in
[386] The level of constant MP was also an important parameter in the early
theoretical models of the MBE by Chiabrera and Bianco [343]. Correlation
between certain "resonant" values of constant magnetic field and
The risk of leukemia was noted by Bauman et al. in [478].

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It took more than ten years for the constant field controlled experimental conditions to become one of the criteria of scientific value of experimental data in the field of magnetobiology. Now one of the reasons for the low reproducibility of magnetobiological experiments, constantly cited by opponents, is clear. Undertaken special studies to identify biologically significant elements of the organization of the electromagnetic environment [703]. Gradually, it was realized that the magnitude of the amplitude of the alternating magnetic field, not necessarily large, in a number of cases also plays a decisive role in observing the effect. This significantly distinguishes the behavior of biological systems in a magnetic field from the properties of oscillators in standard spectroscopy of physical systems. It is precisely this complex behavior of biological systems, which was one of the reasons for the poor reproducibility of experiments, tha rich information about the physical nature of the primary processes of MP reception.

[3] The effect of MP on the weight of the chick embryo on the 10th day of development investigated by Saali, Juutilainen and Lahtinen in [646] under conditions[4]

B(?)Bp(?)b(0–125)f(50, 1000)n(14–28) ,

and also under pulsed action. It was found that both pulsed action and sinusoidal MF lead to MBE. In In the last case, MBE was observed with statistical significance at different amplitudes of the alternating magnetic field. Figure 2.6 shows the results depending on the field amplitude in relation to a constant local magnetic field, the value of which is taken as 50 ÿT. It is noticeable that at At a frequency of 50 Hz, the MBE occurs when the field amplitude becomes comparable to the local field. At a frequency of 1 kHz, the MBE does not exhibit a specific dependence and is generally the same over a wide range of amplitudes. there.

Smith, MacLeod et al. [334] determined the motility of diatom cells in agar with a low content of 40Ca depending on frequency of an alternating magnetic field with an amplitude of 20 ÿT in a parallel constant field of 21 ÿT. A resonance-like increase in mobility by 35 ± 4% was detected at a frequency of 16 Hz, which corresponded to the cyclotron frequency of calcium ions 40Ca2+, Fig. 2.20.

A detailed study of the motility of diatoms under the action of the magnetic field in various modes corresponding to the cyclotron frequency

3The symbol further separates the works, or groups of works, located in chronological order. in a logical order.

4See the designations of the experimental formulas on page 57

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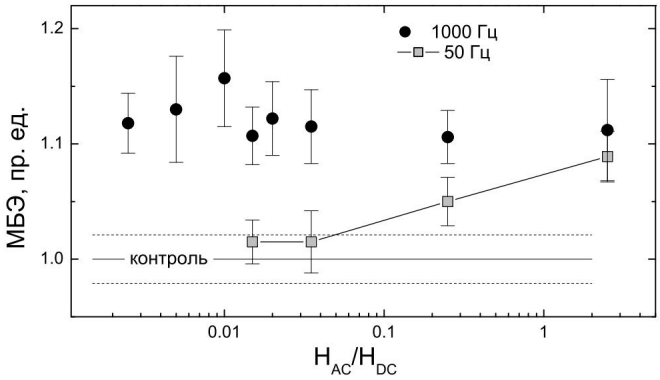


Fig. 2.6: Dependence of the weight of a 10-day old chick embryo on the amplitude of 60 min exposure to variable magnetic field at the early stage of development at different field frequencies, according to [646].

resonance (CR) and its harmonics, was undertaken in [564]. Experimental scheme

B(kf)Bp(?)b(15)f(8, 12, 16, 23, 31, 32, 46, 64)n(> 500)

was chosen so that the magnetic conditions corresponded to the cyclotron resonance of calcium ions Ca2+: k = 1.31 ÿT/Hz. In all
In these modes, a similar in magnitude and statistically significant MBE was found compared to the control in a constant field B (55.7 ± 0.1).
For modes f(8, 12, 16, 23, 31), bell-shaped frequency spectra were measured near the indicated central frequencies.

Kuznetsov, Kshutashvili and others studied the probability of occurrence arrhythmias in frog atrial preparations depending on the frequency
and the amplitude of the magnetic field [106]. The experiments were carried out according to the scheme

B(?)Bp(?)b(0–750)f(0–100)t(30 min)n(7) .

The effect was quasi-resonant in both frequency and amplitude. It reached its maximum at HAC = 15 ÿT, f = 40 Hz, Fig. 2.7.
A relatively large step in changing the MP parameters, as well as the lack of information on the magnitude and direction of the local constant
Magnetic fields complicate the interpretation of the data, but the general nature of the windowed structure of the response is clearly visible. It is suggested that the effect is caused by electric fields induced by the alternating magnetic field.

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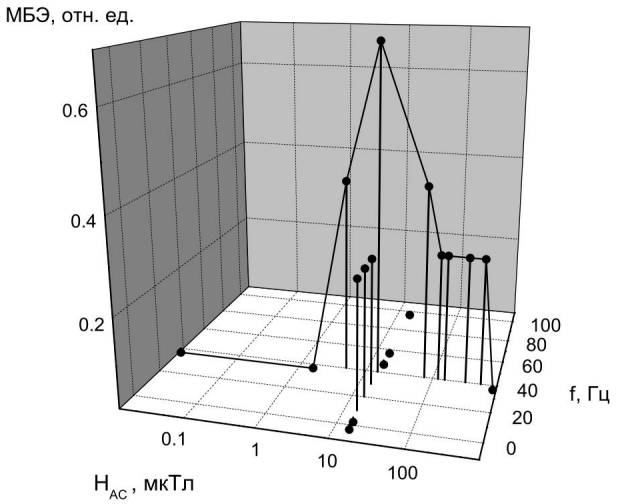


Fig. 2.7: The probability of occurrence of myocardial arrhythmia in a frog depending on the frequency and amplitude of the alternating MP, according to data from [106].

Reese, Fraser et al. [426] reproduced the experiments [334] and confirmed them. They measured the motility of the single-celled algae *Amphora coffeaformis* in agar enriched with calcium ions in concentrations 0.0, 0.25 and 2.5 mM. The experimental design repeated the conditions of [334]

B(21)b(21)Bp(ÿ 0)f(16)n(19)Bsham(43)bsham(< 0.2) .

The large scatter of data did not allow us to record the frequency spectrum of the effect. The results of experiments [334, 426], as can be seen from Fig. 2.8, are in complete agreement with each other. This dependence on the initial concentration shows that some level of calcium disequilibrium is necessary. to observe the effects. At the same time, a high concentration of calcium in the intercellular medium, 5 mM, "switched off" the calcium-dependent MBE, but led to the appearance of MBE under other magnetic conditions, possibly potassium-related [564].

Goodman and Shirley-Henderson also observed frequency, amplitude, and time windows in the effects of low-frequency magnetic fields on transcription processes in human lymphocytes and salivary gland cells. Drosophila [458]. One of the experiments with varying amplitude

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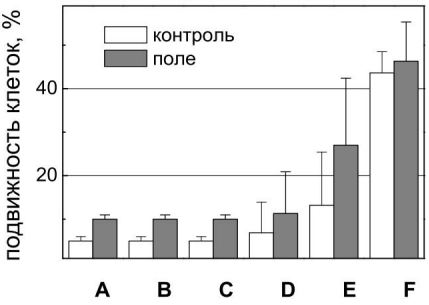


Fig. 2.8: Change in motion
algae cell activity in parallel magnetic fields
at a concentration
(mM) calcium ions in agar 0.0
- A, D; 0.25 - B,E; 2.5 - C,F. By
data [334] - A,B,C and [426] -
D,E,F.

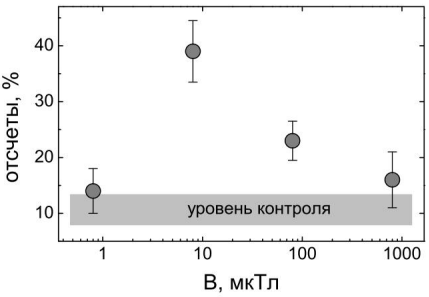


Fig. 2.9: Effect of 20 min exposure to
a 60 Hz magnetic field
of varying amplitude on the process
transcription in HL-60 cells,
according to [458].

The MP was carried out according to the formula

b(0.8–800)B(?)Bp(?)f(60, 72)t(10, 20, 40 min) ,

measured the levels of some transcripts in chromosomes using
by using the radioactive label 35S.

Figure 2.9 demonstrates the dependence of the marker reading level on the MF amplitude. It is evident that the effect is most significant when the amplitude of the alternating MF corresponds in order of magnitude to the geomagnetic field. Maximum changes were observed after 20 minutes of exposure.

The effect of an alternating field at an angle to a constant field on the uptake of a calcium radioactive label in lymphocytes was studied by Lyle,
Wang et al. [335] used cells of various lines, including cancer cells. The magnetic field configuration was

B(16.5 ± 0.5)b(20)bsham(ÿ 0)f(13.6)Bp(? > 20) .

The authors observed a significant effect, Fig. 2.10, when exposed to a horizontal alternating field against a background of an inclined geomagnetic field.
Somewhat smaller, but also statistically significant, changes in

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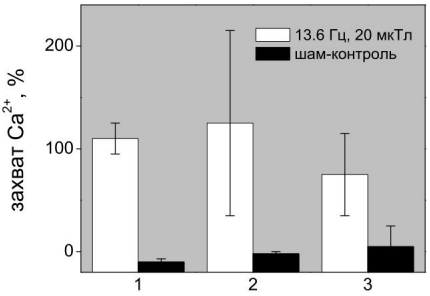


Fig. 2.10: Tilt action low-frequency and constant of MP to capture the 45Ca2+ label in lymphocytes of different types - 1,2,3, according to [335].

observed at a frequency of 60 Hz. Information on the magnitude of the constant field is contradictory. It is reported that its absolute value is 384 ÿT, and the slope to the horizontal is 57±2o. Even if we take into account the probable error in indicating the field magnitude, it is impossible to calculate the true angle between the fields. It is interesting that if a 30-minute exposure to the magnetic field was carried out before the introduction of marks, and not immediately after, the effect was not observed. Perhaps this is due to with the fact that the combination of MP parameters corresponded exactly to the isotope 45Ca. The authors assumed that the frequency they used corresponded to the cyclotron frequency for calcium in a field of 16.5 ÿT, although they did not indicate the isotope number. Moreover, it is hardly fair to calculate this frequency, taking into account only the projection of the constant magnetic field onto some axis, because the other the constant field component in general also affects the dynamics particles.

The experiments of Prato, Cavaliers et al. [546] were aimed at study of the dependence of the MBE on the amplitude of the alternating component of the magnetic field. Snails *Cepaea nemoralis* were placed on a warm surface and measured the time it took the snail to lift its leg. Before taking measurements, the snails were treated with an inhibitor that increased the reaction time; treatment with MP led to a decrease inhibition effect. Experimental design

B(78)b(18–547)f(60)Bp(±0.8)

was selected in accordance with the cyclotron frequency tuning calcium ions 40Ca2+. The magnetic effect in these experiments reached 80% of the relative inhibition value of the bioactive drug, with a data spread of 10–20%. The dependence on the BAC amplitude was polyextreme in nature, Fig. 4.39. Later, the data were confirmed and refined in the works of this group [615, 616], where the experiments were conducted in a double-blind manner. Procedures 1)

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preparation, placement and transfer of animals, 2) exposure in the MP, 3)
reaction time measurements were carried out by different mutually unaware employees. In
[615] a polyextreme frequency
spectrum of the MBE, Fig. 4.36, as well as the dependence on the constant MF at
fixed frequency and amplitude of the variable component.

Blackman, Blanchard et al. [421] conducted a series of experiments to
identifying the dependence of the magnitude of the biological response on the ratio
the amplitude of the variable and the magnitude of the constant collinear
MP. The measured value was the degree of neurite outgrowth inhibition in PC-12
cells. Neurite outgrowth was induced by a biological stimulator. The temperature
was maintained with an accuracy of 0.1 oC. Control was carried out in the same
thermostat in a passive environment.
shielded compartment, which reduced the MP level by two orders of magnitude.
The control was carried out in two ways: with and without a growth biostimulant.
him. The experimental data were normalized according to the scheme,
usually accepted in the presence of two different influencing factors, in
In this case, such factors were a growth stimulator and MP. The relative
magnitude of the MP effect was calculated using the formula

$$\% \text{ NO} = 100\% \frac{R - Z}{N - Z},$$

where Z is the relative number of cells with neurites in the sample in the absence
of MP and stimulator (control 1), N is the same in the absence of MP, but
with a stimulator (control 2), R - the same in MP and with a stimulator. Thus, 0%
and 100% corresponded to the magnitude of the effect when exposing cells in
the absence of MP, without or with a stimulator. Exposure of cells to MP led to
intermediate values. For the formula
experiment

B(36.6)b(10.8–66.2/ ÿ 5)f(45)Bp(< 0.2)n(3–4)g(!) (2.2)

the results obtained are shown in Fig. 2.115 in light
circles show the value of 100% ÿ % NO. Maximum effect
were reliably observed at intermediate values of the amplitude of the alternating
field. Application of the formula

B(2)b(1.1–2.9/ ÿ 0.4)f(45)Bp(< 0.2)n(3)g(!) (2.3)

yielded points closely grouped around the value of 100%, that is, zero effect.

5The author is grateful to K. Blackman for providing the data file.

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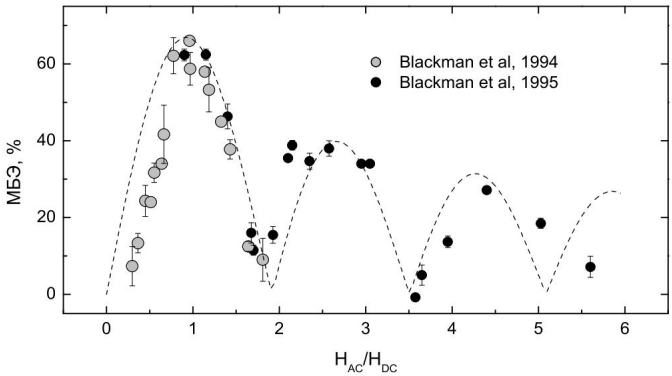


Fig. 2.11: Dependence of the magnitude of the MBE in PC-12 cells on the amplitude variable component in a uniaxial magnetic field, according to data from [421, 488]. The line shows the function |J1(2HAC/HDC)|.

Continuation of the study of the amplitude spectrum of inhibition of neurite growth in the region of large values of the relative amplitude of the MP was carried out in [488]. These data are shown in Fig. 2.11 by solid circles and indicate the polyextreme nature of the amplitude spectrum. The figure also shows the absolute value function J1 (2HAC/HDC). It approximates the experimental data well, so the authors continue to search for physical justifications for this dependence [544].

The authors suggested that the ions Mn(4), V(4), Mg(2)6, as well as less likely, Li(1), H(1) ions may be responsible for magnetoreception of PC-12 cells. It is for these ions in a given by the experimental formula (2.2) at a constant MF BDC and an alternating field frequency f, the cyclotron frequencies ÿc = qBDC/M c are approximately satisfy the relation ÿc = nÿ, ÿ=2ÿf.

In one of the works of this group, frequency spectra were investigated MBE inhibition of neurite outgrowth in the same cells [317]. The main difference was the presence of a perpendicular component of constant MP

B(37)b(5.3–12.5/ ÿ 1.5)Bp(19)f(15–70/5) .

The frequency windows of the MBE were identified at about 40, 60 Hz and above, Fig. 2.12, that is, the polyextreme nature of the frequency spectra of the MBE.

6The valence of the ion is indicated in brackets.

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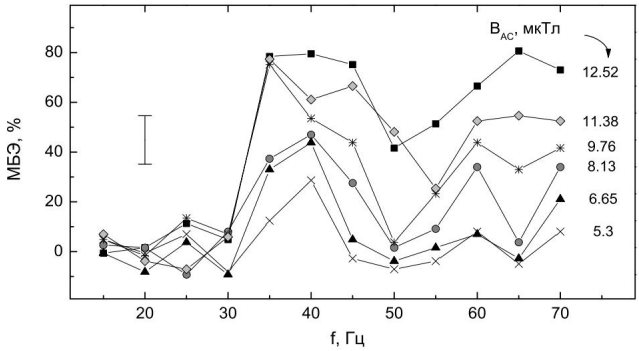


Fig. 2.12: Inhibition of stimulated neurite outgrowth in cells
PC–12 with an inclined orientation of constant and alternating magnetic fields, points are shown for different levels of the amplitude of the alternating magnetic field, according to the data [317].

In parallel fields at a frequency of 45 Hz there was no effect, the authors therefore, they conclude that the component of the constant magnetic field perpendicular to the alternating field is essential. It is interesting that the exact opposite conclusion was made after a special study [277]
the role of the perpendicular constant field in the MBE on another biological system, *E. coli cells.* In [564], the insignificance of the perpendicular component in experiments with the motility of diatoms in a magnetic field was also reported. On the other hand, in [387], it was shown that parallel and perpendicular orientation of fields cause

oppositely directed effects, and their combination can lead to the disappearance of the MBE. Below it will be shown that such complex dependences on the orientation of the fields are characteristic of interference
ions bound in macromolecular capsules

It should be noted that in the experiments [421, 317] a source of alternating magnetic field in the form of a single horizontal ring coil was used. This made it possible to have a number of values of alternating magnetic field at different distances from the ring at once. MP of one frequency in one experiment. This design of the source
The field creates relatively strong magnetic field gradients in the area where biological samples are placed. The literature reports the biological effectiveness of magnetic field gradients in a number of cases. It would be difficult to comment on the experimental data if it were not for the good agreement of the effect sizes in this series of studies with the same

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at different values of the MP amplitude, but at different gradient levels. This indicates the insignificance of MP gradients in the experiments under discussion. In general, in the absence of established mechanisms of action MP, the question of the admissibility of using gradient fields in experiments of this kind remains open.

Lindstrom, Lindstrom et al. [485] found that the sinusoidal MP induces variations in cytosolic calcium concentration in lymphocytes (human leukemic T-cell line). Experimental design

B(50)Bp(53)[B(60)Bp(22)]b(40, 80, 150, 300)f(5, 25, 50, 75, 100).

The variations were similar to the records of a random process, however, some processing of these curves allowed us to establish that the maximum response to the fields from the set indicated in the diagram was an increase in concentration 5–8 times and was observed for a combination of 50 Hz and 150 ÿT in a parallel field of 50–60 ÿT. Unfortunately, the authors did not indicate which value, rms or peak, they used for the alternating magnetic field, and the step size for changing the parameters was quite large. Therefore, attempting to identify the magnetic field target in this case was difficult, although the experiments did reveal a distinct amplitude-frequency window.

The aim of the work of Tofani, Ferrara et al. [429] was to establish oncogenic potential of low-frequency fields. The frequency of formation of intracellular nuclei in human peripheral lymphocytes (HPL) was visually determined. The formation of such nuclei in under special conditions is a marker of chromosomal damage. Experimental schemes

B(±0.1)b(150rms)f(50)[b(75rms)f(32)]

B(42)Bp(±0.1)b(75rms, 150rms)f(32)

allowed us to isolate the value of the constant component of the MP parallel to the variable component. The adapted data are given in Fig. 2.13. The authors noted a statistically significant MBE in the presence of a parallel constant MF, these are the points in the middle of the graph. In At the same time, in general, the data are difficult to interpret because there is little experimental points. The results may not be as bright as in other cases, but this is explained by the fact that the second of the presented MP schemes did not satisfy the condition of maximum interference HAC/HDC ÿ 1.8. Indeed, this value was 2.5 and 5, as it was erroneously The RMS value of the HAC field was chosen rather than the peak value .

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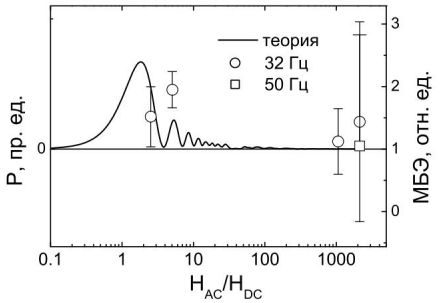


Fig. 2.13: Appearance of markers of chromosomal damage in HPL cells under conditions of parallel LF MF. A typical curve of the ion interference theory is shown.

A series of works by Belyaev, Alipov et al. [246, 353, 245] was devoted to studying the effects of combined magnetic fields on the conformational state of the genome of *E. coli* cells (K12 AB1157) under various magnetic conditions. Specially prepared cell suspensions were subjected to lysis (destruction) after exposure to the MP. Measurements of the viscosity of suspensions was carried out in a rotational viscometer. The measured value was the rotation period of the viscometer rotor. This value is related to the conformational state of the cell genome before lysis. Therefore, the MBE in cells were determined by the relative value of the rotation period for exposed and intact cells. Measurements were taken after one hour after 15 minutes of cell exposure, when the effect was greatest.

In [246] a clearly defined 25% peak of the MBE was observed at the frequency 8.6–8.9 Hz with a width of about 1.6 Hz for the circuit

B(43.6)Bp(19.7)b(30)f(7–12) .

Here, the Earth's geomagnetic field served as a constant field.

Other methods have been used to obtain less than this amount of magnetic energy under these magnetic conditions. pronounced changes in bacterial titer and intensity of synthesis DNA and proteins.

It was also shown that varying the perpendicular component in the range Bp(0–148/4) changed the peak height slightly, by ±5%, and these changes depending on Bp were irregular in nature, [277]. The perpendicular field in these experiments did not play a noticeable role. roles. At the same time, the variation of the parallel field in the range B(126–133/1) resulted in the disappearance of the peak, the MBE was at the level 99 ± 4% over the entire range. The found maximum frequency of 8.9 Hz is close to the fourth subharmonic of the cyclotron frequency of calcium 40Ca, if neglect the perpendicular component of the MP.

In [353] the dependence of MBE on the concentration of cells in

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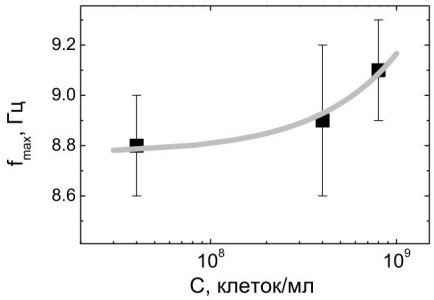


Fig. 2.14: Shift in the frequency of the maximum of the MBE on cells *E. coli* depending on cell concentration, according to [353].

in the range of 107–109 mlÿ1 according to the scheme

B(44 ± 1)Bp(20 ± 1)b(30)f(7.4–10.4)

and found a positive shift in the MBE peaks with increasing cell concentration, Fig. 2.14. The authors explain this observation by the fact that intercellular interactions, the role of which increases with increasing cell concentration, are involved in the formation of the response of the cell population to the combined MP.

Work [245] showed several well-defined frequency MBE windows in the range of 6–69 Hz under the same conditions as above for the magnetic field strength, Fig. 4.32. An important fact was that the frequency The MBE spectra for the standard and mutant *E. coli* cell lines were different. A peak around 16 Hz was observed only for mutant cells. The authors believe that the genome structure, processes involving DNA, are involved in the magnetoreception of these cells.

Garcia-Sancho, Montero et al. [398] investigated the effect of low-frequency magnetic fields on ion transport in several types of mammalian cells. The effect was detected by the uptake of the radioactive label 42K at the CR frequency of the ion of this potassium isotope (15.5 Hz in a field of 41 ÿT) only in Ehrlich cancer cells and human leukemia U937. Label capture 45Ca at the corresponding MF frequency was observed, but was not statistically significant and was not observed for the 22Na label. Experimental design:

B(41)b(25–1000 ± 5 %)Bp(ÿ 0)f(13.5–16.5/1)n(8–24) .

The measurement results are shown in Fig. 2.15. Since there is a non-monotonic dependence on the frequency and amplitude of the variable component MP, these data are suitable for comparison with theoretical calculations.

Note that the non-monotonic dependence of the effect on the amplitude does not agree well with the generally accepted hypothesis about the excitation of quantum transitions by variable magnetic fields against the background of a constant field.

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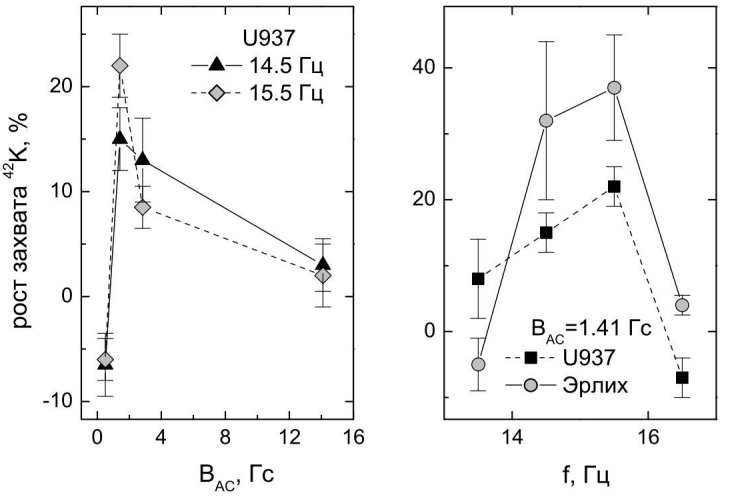


Fig. 2.15: Effect of one-hour exposure of cancer cells to magnetic fields of different amplitudes and different frequencies on the uptake of radioactive ions potassium isotope 42K, according to [398].

when transitions are excited, their intensity is saturated with increase in the field amplitude.

The perpendicular combination of MP was used by Picazo, Valejo and Bardasano in [602] when observing MBE in chronic (3 months) irradiated mice

B(40)Bp(141)f(50) .

The number of leukocytes in the blood of the experimental group was 9.3+6.2 thousand/ mm3, and the control group thousand/mm3, groups are statistically significantly different (Bp = 0) was 13.3+5.7 . Qualitative and quantitative changes in the composition of lymphocytes were identified with MP-induced leukemia.

In the work [670] Spadinger, Agnew and Palcic took into account that the cytoskeleton responsible for the shape and motility of cells contains molecules that are changed by the Ca2+ mediator. Since MP acts on calcium transport *in vitro,* it can also change cell motility. The authors studied the motility and morphology of fibroblasts before, during and after four hours of exposure to low-frequency magnetic resonance. Measurements were carried out on a computerized microscope equipped for creation of MP with one ring winding covering a Petri dish.

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Experimental formula

B(28.3)b(141 ± 21)Bp(6.4)f(10–63/2)n(ÿ 80)g(< 10 ÿT /cm) .

No statistically significant differences were found between exposed and sham-exposed cells for all
frequencies.

The authors note that the negative result could be a consequence of unaccounted environmental humidity parameters, uneven illumination of the cells by the microscope lamp, and the lack of proper metabolic
cell states.

Observation of such MP effects requires parameter adjustment
MF, specific combinations of different parameters simultaneously: constant MF, amplitude of the coaxial alternating field, perpendicular component, frequency, as well as the smallness of background variations of the field and gradients. Therefore, the reasons for the lack of effect here could be would add a relatively large gradient of the constant field, so that the difference in fields for one sample of cells systematically amounted to 30%.

In [144] Novikov and Zhadin report on the effect of action parallel fields when scanning frequency, 0.1 Hz/s, into L-shapes solutions of asparagine, arginine, glutamic acid and tyrosine in bidistilled water. The measured value was the current in the electrochemical cell. The effect consisted of the appearance of a single maximum of 30–50% on the current–frequency dependence near cyclotron frequencies for the corresponding molecules. The results are presented in Table 2.1, where the MF values are given in μT.

The authors note the ambiguity of the physical mechanism for the increase in current at cyclotron frequencies corresponding to the molecules of these amino acids containing ionizing amino groups. It should be noted that
resonance-like responses in a similar "electrochemical" configuration were observed in a suspension of yeast cells in a geomagnetic field when scanning the frequency of the electric field [370, 587]. In the latter
In this case, the frequency maxima corresponded not to cyclotron frequencies, but to NMR frequencies
frequencies.

A more complete study was carried out in Glu solution in [142].
Some of the Glu molecules were ionized by adding hydrochloric acid to the solution. A solution without Glu and a solution with the same concentration were used as a control. concentration of acid, which ensured a zero electrokinetic potential of Glu, that is, their immobility. They used

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Table 2.1: Effect of magnetic field on the conductivity of amino acid solutions. data [144]

Frequency	b B	Bp	Solution	Frequency max, Hz	
0.1–40	0.05	25	0	Asn	2.9 ± 0.1
				Arg	4.4 ± 0.1
				Glu	2.5 ± 0.1
				Tir	4.4 ± 0.1
				H2O	no effect
		0	25		no effect
			0		no effect
	5	25	0		no effect

slow frequency scanning 0.01 Hz/s at

B(30)b(0.025)Bp(< 1)Ep(8 V/m)f(1–10) .

The maximum current was observed near the cyclotron frequency of 3.11 Hz, for Glu in a field B = 30 ÿT. The width of the maximum was approximately 0.05–0.1 Hz. The author also performed gel chromatography of the solution treated with MP with effective parameters and noted the formation of under these conditions, the condensation products of Glu monomers. The results of the chromatographic analysis apparently indicate that the observed The effects are due to the properties of the Glu molecules in solution, not on the electrode surface. To explain the effect, it is suggested that the target of the magnetic field action is clusters or polyions of amino acids, for which the cyclotron frequency is the same as that of an individual molecule.

Solutions of L-asparagine Asn 7.57 · 10ÿ3 M/l in acidified bidistillate at pH = 3.2, T = 18 ± 0.1oC were studied in [143] according to the scheme

B(30.34 ± 0.16)b((20 ± 2) 10ÿ3)Ep(5 mV/cm)f(3.38–3.62/0.01).

When the alternating field was turned on, a current pulse was observed in the cell, which relaxed for 50 seconds. After that, the field was turned off, the frequency was adjusted by 0.01 Hz and the field was turned on again. The results are shown in Fig. 2.16, constructed according to the data of [143]. Noteworthy is the very small magnitude of the alternating magnetic field, of the order of 20 nT, and the non-stationary nature of the response, indicating about the rearrangements of the molecular structure of the solution. The electric field in this experiment was an order of magnitude smaller than in [144, 142], without visible consequences for observing the effect. This suggests that

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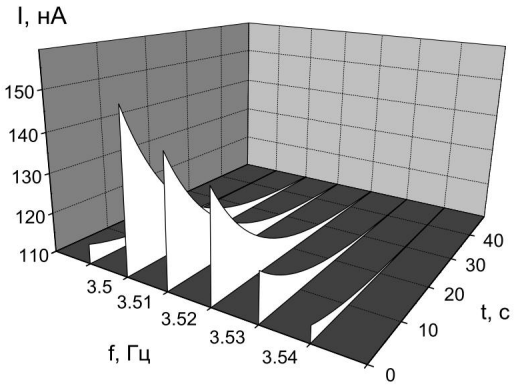


Fig. 2.16: Current pulses in an electrochemical cell with an asparagine solution in a constant magnetic field of 30.34 ÿT when a parallel alternating magnetic field with an amplitude of 20 nT is connected, according to data from [143].

the electric field in these experiments is only important for measuring the effect. As the solution temperature increases to 36oC, the value current pulses fell.

Some questions important for clarifying the physical nature phenomena are not covered in these works. In particular, it is interesting to know: a) was an electric field applied to the solution when the formation of polymer molecules was studied and b) does the frequency of the maximum effect depend on the pH of the solution? The charge of the amino acid zwitterion changes depending on the acidity of the medium.

The effect of pulsed magnetic field on *the lac operon* enzyme system of the Escherichia *coli* line NCTC9001 was studied by Aarholt and Flynn and Smith [229] measured the transcription rate of the ÿ-galactosidase gene, suppressed by a repressor protein that prevents the polymerase from approaching the corresponding DNA region. Control cells were placed in a soft magnetic metal container. Experimental cells were exposed for two hours to rectangular magnetic field pulses with a frequency 50 Hz. The dependence of the synthesis rate on the pulse magnitude was recorded in the range of 200–660 ÿT.

The rate of synthesis of exposed cells deviated from the control level: at a pulse strength of about 300 ÿT, it decreased fourfold; at 550 ÿT, it increased two and a half times.

Fig. 4.46. An extreme value of the MBE from the concentration was noted.

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cell concentrations in suspension. MBE was observed in the range of 2.5–5.5 x 107 mlÿ1, that is, with a distance between bacteria of about 30 microns, which is more more than fifteen times their size. The authors pointed out the importance of intercellular interactions and suggested that the observed MBE is associated with changes in the activity of the repressor protein.

Reinbold and Pollack used modulated MPs in [628], B(20)b(20)f(76.6), with a frequency close to double the cyclotron frequency for 39K and triple for Mg, as well as an MP with a cyclotron frequency calcium, B(130)b(250, 500)f(100). These fields increased, by 2–2.5 times (P< 0.05), the calcium concentration spikes in rat bone cells, recorded by fluorescence microscopy. Interestingly, the presence of the effect depended on the orientation of the MP, horizontal or vertical, and from the presence of calcium in the cell culture serum.

Litovitz, Penafil, and others studied the role of constancy in [641] parameters of the MP signal in the cellular response. The measured parameter ornithine decarboxylase activity was measured in L929 cell culture. The constant field was not measured, but the experiments were carried out in a mu-metal box with a 5-fold weakening of the external magnetic field, so that the approximate value could be about 10 ÿT. Magnetic fields with frequencies of 55, 60 and 65 Hz (10 ÿT) produced approximately equal activity doubling effects. However, the 55/65 Hz switching mode was effective only if the holding time of each frequency was exceeded 10 s. Mode with switching amplitudes of 0/10 or 5/15 ÿT was also effective starting from 10 s switching interval. On the other hand, if the 60 Hz 10 ÿT MF signal was interrupted every second for a time longer than 0.1 s, then the biological effect did not appear. The dependence of enzyme activity on the pause time and the MP switching interval is shown in Fig. 2.17.

The authors conclude that there are two time scales in the cellular system, 10 s and 0.1 s, which characterize memory, respectively. cells for the constancy of exposure conditions and detection time MP signal.

Two-hour exposure in a magnetic field with a 1/f spectrum in the range of 10ÿ3–10 Hz significantly reduced the cell adhesion index, proportional to the surface negative charge of cells, by 30% compared to the control [140]. Cell sedimentation was also accelerated, the density of supercoiled packing of nuclear DNA increased. At the same time, MF of similar intensity but different spectral composition (white noise, 0.8 Hz square wave, 50 Hz sinusoidal field) did not cause

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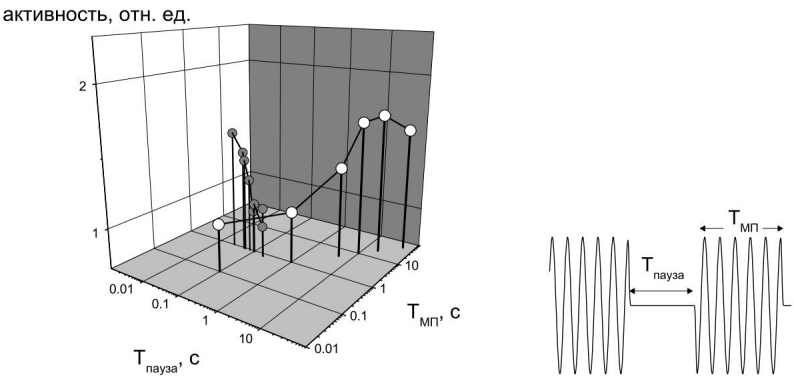


Fig. 2.17: Ornithine decarboxylase activity of L929 cell culture as a function of the parameters of the intermittent sinusoidal MF 60 Hz 10 ÿT, according to [641].

biological effects.

Muzalevskaya and Uritsky [140] believe that the shape of the 1/f spectrum is an essential property of the magnetic field, which determined the occurrence of the effect. They meant a certain “resonance” with the 1/f eigenvalues processes in cells, for example, ion currents. Questions of primary biophysical processes of magnetoreception were not discussed. How will it become It is clear from the results of Chapter 4 that the data [140] can be explained on the basis of mechanism of ion interference.

Dependence of DNA mobility of rat brain cells on the amplitude of the magnetic field B(?)Bp(?)b(100, 250, 500)f(60) during two-hour exposure to against the background of uncontrolled local static MP was observed in [516].

Katzir and Parola [503] studied the proliferation of chick embryo fibroblast cells under magnetic conditions

B(?)Bp(?)b(60–700)f(50, 60, 100)n(ÿ 100)

and found a polyextremal dependence of the response to 24-hour exposure, Fig. 2.18.

Various means of measuring proliferation, including a hemocytometer, spectrophotometer, and radioactive labeling, yielded similar results. The effect increased in the range of high amplitudes and frequencies.
is probably associated with the electrochemical action of induced currents, since the product bf exceeds the established limit (1.3).

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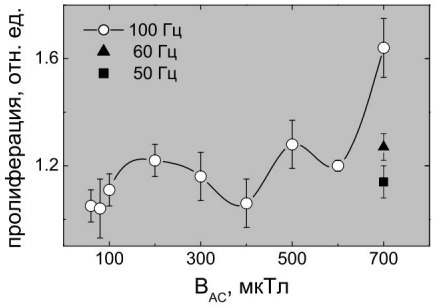


Fig. 2.18: Amplitude dependence of fibroblast cell proliferation in MP of different parts
hundred.

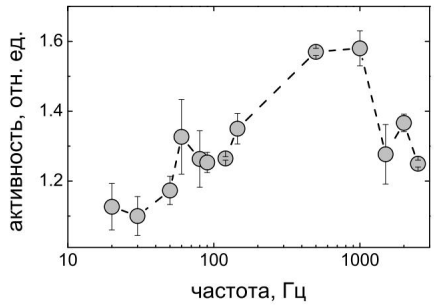


Fig. 2.19: Frequency spectrum of the activity of cytochrome oxidase from rat liver in a magnetic field of 10 ÿT. Averaging the results [325].

Data on the magnitude and direction of the constant magnetic field are not provided, so it is difficult to comment on the possible ion target.
MP, however, the extremum in the region of 200 ÿT generally corresponds to the manifestations of the ion interference mechanism.

Frequency spectrum of the effect of magnetic fields with an amplitude of 10 ÿT on activity cytochrome oxidase, a membrane enzyme, was measured by Blank and Soo in work [325]. The activity was measured spectrophotometrically by the concentration of the oxidized form of cytochrome C. Data on the local constant MP are not presented. The frequency dependence of the effect revealed
maximum in the region of 500–1000 Hz, Fig. 2.19. This spectrum is obviously incompatible with the characteristic ionic frequencies. It is assumed that the MP
acts on the mobile charge inside the enzyme, and the position of the maximum of the frequency spectrum corresponds to the time of a single cycle of the enzymatic reaction.

2.3.2 Participation of some ions in magnetoreception

Since it was established that biologically effective frequencies of magnetic fields approximately correspond to the cyclotron frequencies of different

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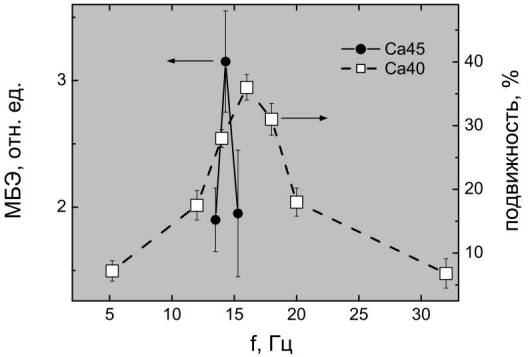


Fig. 2.20: 1 - incorporation of the 45Ca label into human lymphocytes, [332], 2 - motility of diatom cells in agar with a low content of 40Ca, [334], depending on the frequency of the alternating magnetic field with an amplitude of 20 ÿT at a parallel constant field of 21 ÿT.

ions, their harmonics and subharmonics, and shift proportionally the magnitude of the constant magnetic field [524, 527], the participation of certain ions in the formation of the response of a biological system is discussed in many works on magnetobiology. The important role of calcium ions Ca2+ is practically universally accepted due to the abundance of experimental results comrade

The involvement of other ions is not so obvious and is a matter of debate, as how the same effective frequency can simultaneously correspond to a harmonic of one ion and a different harmonic of another ion. It is impossible to determine the ion by the shift in the frequency of the maximum depending on the constant magnetic field in this case, since both hypotheses give the same prediction. Obviously, the isotopic shift
There is a regular way of identifying ions at the maxima, but these Experiments are expensive and not always possible. Only a few are known. works, where the calcium ion was identified as a target for MP by the shift of the peaks of the MBE with the isotopes 40Ca [334] and 45Ca [527], Fig. 2.20. The frequency ratio of the maxima 16/14.3 is close to the ratio 44.95/40.08 masses of the isotopes 45Ca and 40Ca. The value of this result is somewhat reduced by the fact that the MBE spectra of different biological systems were compared.

Radioactive isotopes of elements are usually used as labels that allow us to take into account the intensity of metabolic processes involving substances supplied with this label. 3H isotopes were used

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[697, 199, 246, 250, 350], 32P [656], 35S [458], 45Ca [268, 267, 228, 586, 484, 729], 22Na and 86Rb [659], 125I [600]. Unfortunately, even if MBE is observed, this fact in itself does not prove that the data Isotopes are targets of the magnetic field. Indirect identification of ions is associated with attempts to observe changes in the conductivity of the corresponding ion channels in the magnetic field [659, 324].

Calcium

It is well known that calcium ions act in many biological processes such as synaptic transmission, secretion, ciliary motility, enzyme activation, processes of muscle contraction, reproduction, growth and development. Intracellular calcium concentration is ~ 10ÿ8–10ÿ6 M per four

An order of magnitude lower than in the external environment and is maintained by several membrane mechanisms. This ensures the operation of rapid signaling mechanisms responding to external conditions. The protein calmodulin, which influences the activity of many enzymes, is particularly sensitive to the concentration of intracellular calcium.

Kislovsky [107] suggested an important role for calcium in the biological effects of EMF. Apparently, the works of Bowen, Kaczmarek and Adie [268] and Bowen and Adie [266] were the first experiments to find a link between the biological effects of EMF and calcium ions. In these In studies, changes in the rate of calcium ion release from brain tissue were observed when exposed to low-frequency, radio-frequency, and microwave EMFs. Later, these data were obtained by independent experimental confirmation. Calcium binding to calmodulin as a primary microwave biological target and biochemical analysis This hypothesis was discussed by Arber in his work [249].

Experiments by Hojerick, Sandblom, and colleagues [333] were aimed at testing the hypothesis that the interaction between the MP and the body occurs in calcium ion channels. The total Ca2+ current through micropatches of cell membranes was measured when clonal insulin-producing ÿ-cells (RINm5F) were exposed to a combination of DC and AC magnetic fields in the frequency range of 10–
60 Hz, including the cyclotron frequency of 16 Hz (for Ca2+ in the BDC field = 20.9 ÿT, HACpeak = HDC, HDCHACz). This field was chosen due to its found efficiency. The 50 Hz background field did not exceed
70 nT, the geomagnetic field was compensated. The transport of Ca2+ ions through protein channels of the plasma membrane did not show resonance.

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behavior in the frequency range studied. This indicates that
that in the case of magnetically sensitive calcium processes the target
It is not ion channels that are most likely responsible for the action of MP, but some other ones biophysical systems.

Jenrow, Smith and Libow [491] found another successful biological system for observing the magnetobiological effect. They
studied the process of regeneration of the severed head in the planarian worm *Dugesia tigrina.* Regeneration involves many of the processes
cellular signaling involving Ca2+ ions and therefore, according to the authors, is a convenient experimental model. The measured parameter was the regeneration time, recorded by the appearance of pigment spots at the site of future eyes. Under certain conditions of exposure to magnetic fields, the regeneration time increased by approximately
140 to 180 hours. The experiments were designed to test the hypothesis
(see [527, 695]) that electric currents induced by alternating magnetic fields are the physical cause of the occurrence of MBE.

The first experiment was carried out according to the following two schemes simultaneously, and the level of the MP gradient in the experimental area was not exceeded 10ÿ2 ÿT/cm

A1) B(78.42 ± 0.18)b(10)f(60)Bp(10ÿ2 ± 10ÿ1)N(69)

A2) B(10ÿ2 ± 5 10ÿ2)b(10)f(60)Bp(10ÿ2 ± 10ÿ1)N(70) .

The second experiment was conducted using two different designs.

B1) B(51.13 ± 0.12)b(51.1)f(60)Bp(5 10ÿ2 ± 5 10ÿ1)N (92)

B2) B(10ÿ2 ± 2 10ÿ2)b(51.1)f(60)Bp(10ÿ2 ± 5 10ÿ2)N(91) .

The third experiment involved exposure to the local geomagnetic field with control of industrial frequency background level

C) B(18.2 ± 10ÿ2)b(5 10ÿ3)f(60)Bp(53.5 ± 10ÿ2) .

Schemes A1 and B1 corresponded to the CR conditions for Ca2+ and K+ ions respectively. The temperature was maintained with an accuracy of ÿ 0.05oC.
The measurement results for all circuits are shown in Fig. 2.21.

It was concluded that the delay in regeneration is apparently initiated at an early stage of regeneration before the initiation of proliferation processes.
and differentiation, and is caused by Ca2+ ions. It was shown that the observed MBE is not a consequence of the induced electric field and eddy currents. This conclusion is based on the fact that 1) there is

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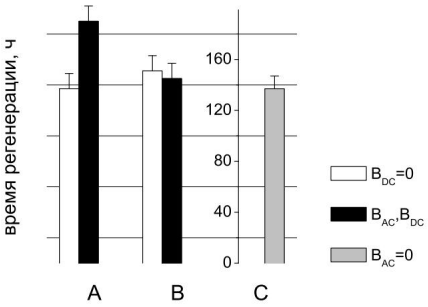


Fig. 2.21: Average regeneration time of planarians in parallel magnetic fields at a temperature of, oC: A — 22, B — 20, C — 22. Based on the results [491].

the difference in MBE for schemes A1 and A2, while the level of induced the electric field is the same, 2) there is no difference in the MBE for schemes A2 and C, while the electric field level is different, 3) MBE in circuit A1 magnitude is greater than in circuit B1, while the ratio of electrical fields are inverse, 4) direct calculation of the level of the induced electric field in an oriented planarian gives a value of three orders of magnitude less than a known threshold value.

Smith, MacLeod and Libow [667] tested the hypothesis of the involvement of various cations, Ca, Mg, K, in the change in the growth of seeds of garden radish *Raphanus sativus. var. Cherry Belle* under conditions of continuous exposure to parallel MF. Exposure according to schemes

$$\begin{aligned} &\text{Ca } N = 1, 2, 3\ B(78.4, 39.2, 26.1)b(20)f(60) \\ &\text{K } N = 1, 2, 3\ B(153.3, 76.6, 51.1)b(20)f(60) \\ &\text{Mg } N = 1.5\ B(47.5, 9.5)b(20)f(60) \\ &\text{controls} \qquad B(0)b(20)f(60)\ ,B(geo)b(0)\ , \end{aligned} \tag{2.4}$$

where N is the harmonic number of the cyclotron frequency, made it possible to isolate contributions of ions to various growth parameters. The strongest, 70–80% change compared to the control was experienced by the root weight at the end 21-day exposure period. Other parameters did not change so much. significantly, but statistically reliable. They turned out to be effective tuning to the cyclotron frequency and its harmonics for all the indicated ions, with the maximum effect observed when tuning to calcium. The efficiency of tuning to odd harmonics was significantly higher compared to the same for the second harmonic.

The sign of the effect, that is, a decrease or increase in the measured growth parameter, depended both on the type of ion on which the effect was expected and on the selected parameter (stem length, leaf width, etc.) etc.). However, no pattern could be established here.

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The authors believe that these experiments confirm the mechanism of cyclotron resonance in magnetobiology. Unfortunately, these experiments
difficult to interpret in terms of the ion interference mechanism discussed below, since the parameter b/B, which is important for this mechanism, changed significantly in the experiments described.
zom.

Sisken, Shahideen and Sisken [663] measured the luminescence of photoprotein introduced into cells before, during and after two to three hours
exhibitions in MP

B(?)Bp(?)b(300–71700)f(16–180) .

Intercellular calcium concentration and other calcium-dependent
processes in ROS 17/2.8 cells did not change under the influence of MP. The absence of MBE was probably due to the rather high level
An alternating magnetic field, the lower value of which was six times greater than the geomagnetic field, was measured. Nothing was reported about the unquestionably important parameters of a constant magnetic field. Furthermore, ferromagnetic concentrators, which typically produce large magnetic field gradients, were used to obtain alternating magnetic fields.

The role of calcium processes was also discussed in [228, 505, 564, 335, 426, 185, 708, 729, 357, 398, 670, 79, 628, 643]. In [568] it is reported that by 1992 at least 11 different research groups
observed the effect of low-frequency magnetic fields on calcium regulatory processes.

Magnesium

Some calcium-binding proteins are also capable of binding magnesium. [522], and the bond sites for calcium and magnesium can be identical [372]. Therefore, Mg2+ ions , along with calcium ions, are considered
as potential MP targets.

Long-term exposure to parallel MFs tuned to the cyclotron frequency of magnesium and its fifth harmonic resulted in 10–70%
changes in the growth parameters of garden radish [667], see (2.4).

Deryugina, Pisachenko and Zhadin [79] studied the motor and exploratory activity of rats in an “open field”. The animals were placed in a constant magnetic field and a parallel alternating field. Frequency
the latter was chosen from a number of cyclotron and Larmor frequencies for ions of magnesium, calcium, sodium, potassium, chlorine, lithium and zinc

B(500)b(250)f(380, 630)Bp(< 50) .

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Only for the cyclotron frequencies of magnesium and calcium was the effect detected.

Magnetobiological effect on planarian worms at CR frequency
magnesium ions were observed by Lednev, Srebnitskaya et al. in [129] according to the scheme

B(20.9 ± 0.1)b(38.4 ± 0.1)f(20.4–32.4)) .

The characteristic bell-shaped form of the frequency spectrum of the MBE is shown in Fig. 4.35.

Sodium

Libow and Parkinson [526] attempted to detect MBE in the intestinal tissue of the turtle *Pseudemys scripta* using a parallel configuration of constant and alternating fields with cyclotron frequencies.
sodium ions 23Na and others. The transepithelial potential was measured
for fixed values of MP in a wide range of frequencies and fields:

B(10–220)b(1–20)f(3–770) .

No changes in potential were detected. The authors attributed this to a number of factors, including the absence of artificial nonequilibrium in ion concentration, which was a prerequisite for reliable observation.
MBE with calcium participation.

Potassium and rubidium

Apparently the first observation of extreme MBE when tuning to the cyclotron frequency of potassium was made in [564] by MacLeod,
Smith and Liebow. In the experiment

B(41)Bp(?)b(15)f(16)n(> 300)

observed a decrease in the motility of diatom cells
agar with a high calcium concentration, which initially ensured maximum motility. Control samples were kept in a constant magnetic field of 55.7 ÿT. Responses were also detected at 3, 5, and
15 harmonics of the cyclotron frequency and were not detected at the rest of the harmonic series from 1 to 17.

Subsequently, this group of authors confirmed the effectiveness of exposure to parallel magnetic fields when tuned to the 1st and 3rd harmonics of the cyclotron frequency of potassium on radish seeds [667], see (2.4).

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Statistically significant change in potassium isotope ion uptake
42K in mammalian cells in both parallel and perpendicular magnetic field orientations was observed in [398], at a certain value of the field amplitude, Fig. 4.42. The frequency of the maximum corresponded to the cyclotron frequency of this ion, which indicates the possible participation of potassium processes in some magnetobiological effects.

Experiment [491] did not confirm the involvement of K+ ions as targets
MP in the process of regeneration of planarian worms, although in [179] their probable involvement in MBE with regenerating planarians is discussed.

In [506], Cavaliers, Prato and Thomas studied the change in opioid-induced analgesia in the land snail under the influence of 15
min exposure in parallel MP when configured for cyclotron
frequency of potassium ions K+

B(76.1)f(30)b(0 ± 0.2, 38.1, 114.2, 190.3, 213.1)n(23–46) .

The effect size reached 27±4.2%. In the b(190.3) mode, MBE was eliminated by treating snails with glibenclamide, a potassium antagonist.
channels. The authors note that the cyclotron frequency of potassium is very close to the second subharmonic of the cyclotron frequency of calcium, which makes it difficult to separate the effects between these ions.

Some experiments use a radioactive isotope
86Rb. The rubidium ion Rb+ is similar in properties to the K+ ion. Their ionic radii are 1.49 and 1.33 Å. ^{o} accordingly and noticeably different from
radius of the sodium ion Na+ 0.98 A ^{o}. Therefore, when studying the properties of the membrane ion pump, the protein Na,K-ATPase, in an alternating electric field in [659], they used the replacement of part of the K+ ions with Rb+. This
made it possible to show that in an alternating electric field only the K+ part of the pump is activated and the protein can work as two
independent pumps.

The authors used an electric field of e(20 V/cm)f(1000). It is interesting to assume that the combined magnetic field could affect
ions and isotopes of rubidium in such experiments, since potassium ions as
MP targets were the subject of experimental consideration.

In the work of Ramundo-Orlando, D'Inzeo et al. [388] for observation
To study the effects of low-frequency magnetic fields in a non-living system, a suspension of liposomes was used—artificial cells that simulate red blood cells.
The diffusion rate of p-nitrophenyl was measured spectrophotometrically.
acetate (p-NPA). The diffusion rate is related to the enzymatic activity

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carbonic anhydrase activity captured by the liposomes during their preparation. The surface of the liposomes also contained stearylamine, a lipid interacting with other proteins of the system. Exposure diagram included parallel constant and variable MP:

B(50 ± 0.5)b(25–75)f(4–16)n(15)g(< 1%) .

Control measurements were carried out in the geomagnetic field B(22.4)b(< 0.5). The experiments were repeated on two installations in two different buildings. 60-minute exposure at a frequency of 7 Hz at B(50)b(50) resulted in to an increase in the diffusion rate of p-NPA from the control level of 17 ± 3% to 80±9% (100% for destroyed liposomes). Frequency spectrum of the effect contained bright maxima at frequencies of 7 (main) and 14 Hz. The effect disappeared if only constant or only variable MP.

The authors suggest that the positive charges of stearylamine on the surface of liposomes are targets for external MP. Binding of these charges by alkalization of the environment from pH 7.55 to 8.95 led to the disappearance of the effect.

Note that in a constant magnetic field of 50 ÿT, the frequency of 7 Hz is close to the cyclotron frequency of rubidium and the Larmor frequency of potassium, and 14 Hz is close to the cyclotron frequency of potassium.

The change in the capture of potassium and rubidium labels under the influence of electromagnetic fields is shown in [395]. The possibility of MBE with the participation of potassium discussed in [125].

Lithium

Thomas, Schroth and Liebow used in [696] mutually perpendicular constant and variable MP. A certain conditioned reflex was preliminarily developed in five rats over several months.

The experiment consisted of making rats perform this standard procedure immediately after 30 minutes of magnetic resonance irradiation. Magnetic resonance parameters selected based on the expected tuning to the cyclotron frequency of lithium ions Li+

B(26.1)bp(ÿ 70)b(?)f(60) .

The presence of a small BAC component parallel to the constant field was noted . Some behavioral responses of rats associated with the acquired conditioned reflex were changed under the influence of the magnetic field, Fig. 2.22

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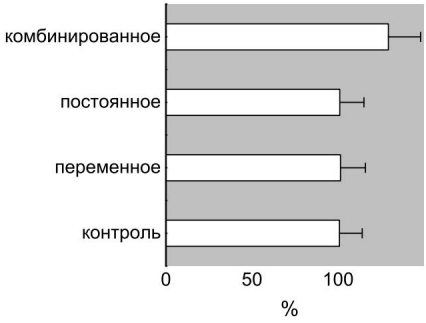


Fig. 2.22: Reaction index of rats for 30 minutes of MP action, according to data [696]. Levels: control — GMP, only BAC 60 Hz, only BDC = 27.1 ÿT, combined BAC + BDC action .

shows the average data for five rats. It is clear that significant changes occur only with the combined action of constant and variable fields.

Blackman, Blanchard et al. [387] observed MBE using the formula

$$b(18.7–48.6)Bp(36.6)B(< 0.2)f(45) .$$

From the point of view of resonant interference of bound ions (interference in perpendicular fields), the effect is possible on the Larmor frequency. In the given constant magnetic field, the Larmor frequency of only ions lithium, 40.5 Hz, close to that used in the experiment.

In the work [644] Ruzik, German and Gogala investigated the effect of physiological stress factors (lack of water) on sensitivity germination of spruce seeds to a combined MP in a perpendicular orientation

$$B(46 \pm 4)bp(26 \pm 4, 105 \pm 10)f(50) .$$

A 10–50% slowdown in MP-induced germination was observed. under stress conditions and absence or slight acceleration of the effect outside stress conditions. Note that the MF frequency used is equal to the Larmor frequency of lithium ions at a given level of constant MF.

An explanation of the characteristic form of the amplitude spectra of the MBE measured in [421, 488], with the first maximum in amplitude near the values of HAC/HDC ÿ 0.9, is also possible based on the assumption that involvement of lithium ions in magnetoreception of PC-12 cells [300], see Section 4.5.

The possible role of lithium ions in MBE was discussed in [665, 480].

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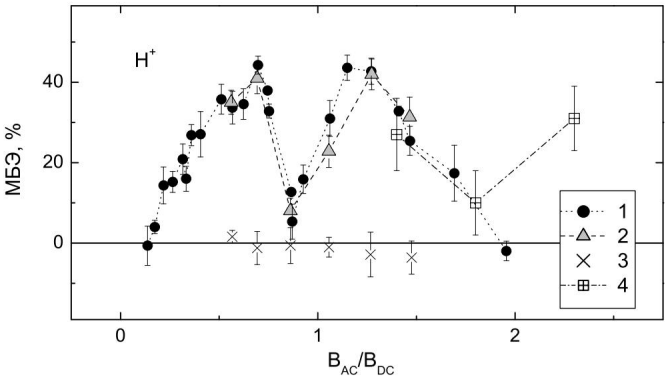


Fig. 2.23: Magnetobiological effect under cyclotron conditions hydrogen ion resonance: on PC–12 cells - 1, 2 (outside resonance - 3), according to [551]; on regenerating planarians - 4, according to [465].

Hydrogen

Changes in the rate of neurite outgrowth on PC-12 cells in magnetic conditions corresponding to the CR of a proton or hydrogen ions 1H+ were observed by Trillo, Ubeda et al. in the work [551]. The amplitude spectra of the MBE were studied under conditions differing in the magnitude of the constant and the frequency of the alternating field

1) B(2.96)f(45)b(0.41–5.81)Bp(< 0.2)
2) B(1.97)f(30)b(1.12–2.9)
3) B(1.97)f(45)b(1.12–2.9) .

For comparison, the spectrum was also taken under conditions that did not correspond to cyclotron resonance.

The measurement results are shown in Fig. 2.23. As can be seen, the cells do respond when the frequency is tuned to ÿc. Good correspondence of points 1 and 2 obtained at different levels of constant MP, but “in resonance”, indicates that the MP gradients, which varied both from group to group, 1 and 2, and for different points within groups, were not a biotropic factor here.

This graph also shows three points - measurements of the intensity of mitoses in the cells of a regenerating planarian when tuned to the CR

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in significantly larger MPs, B(44), [465].

The authors [551] believe that the location of the points indicates the presence of two different mechanisms of the MBE. One of them causes a relatively slow rise and fall of the MBE with an increase in the relative amplitude of the MF from approximately zero to two and, in general, follows the course of the Bessel function J1(2BAC/BDC). The other is responsible for the sharp "dip" of the MBE in the center of the graph. Adie and Bowen [240] believe that ions
hydrogen could replace calcium at its binding sites.

The effect of parallel magnetic fields with the frequency of proton magnetic resonance on the proliferation of neoblast cells in regenerating planaria was observed by Lednev, Srebnitskaya et al. [179]. The planaria were cut off
the head part of the body and placed the experimental animals in the MP for 24 hours, and control in MP without a variable component. Then the number was measured
mitoses of cells extracted from the area of regenerating tissue. Experiments were carried out according to the following schemes to identify the dependence of the magnetobiological effect on the amplitude and frequency of the variable component of the magnetic field

B(20.87 ± 0.01)b(0–80/ ÿ 20)f(889)

B(42.74 ± 0.01)b(78.6 ± 0.8)f(1808–1830/ ÿ 3) .

The frequency dependence had a characteristic resonance shape with a maximum at the proton NMR frequency and a width of about 10 Hz. The dependence
The effect on the amplitude also had a maximum at a ratio of the amplitude of the alternating field to the magnitude of the constant field of 1.8. The magnitude of the effect at the maximum was about 47±10%, Fig. 4.33, 4.43. The authors made special efforts to take into account the diurnal variation of the geomagnetic field.
It should be noted that the magnetic conditions of the experiment excluded NMR, since the alternating and constant fields were coaxial.

It was suggested that the targets of the magnetic field in these experiments are the spins of hydrogen nuclei that are part of intraprotein hydrogen bonds. The earlier assumption about the important role of hydrogen atoms in
magneto-dependent biological reactions on yeast cells were done in [370, 587], where biological effects were observed at frequencies corresponding to 1H NMR in a geomagnetic field. Theoretical
The rationale for such effects was discussed in [609, 291].

In [374], Blackman, Blanchard et al. reproduced the data [551]
and also determined the dependence on frequency near the maximum of the MBE (neurite outgrowth on PC-12 cells) when tuned to cyclotron

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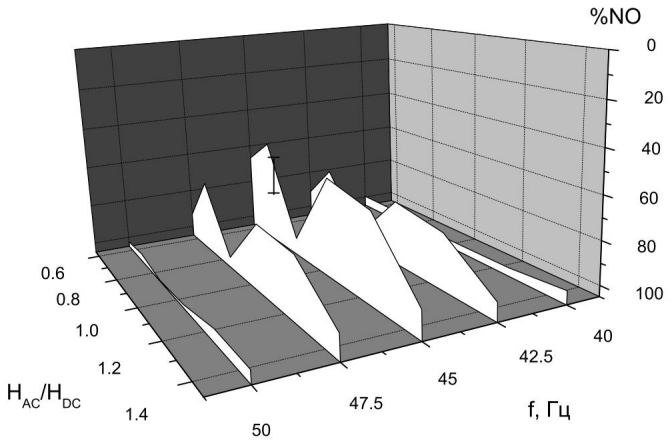


Fig. 2.24: Effect of uniaxial magnetic field daily exposure on neurite growth in nerve cell culture when tuned to cyclotron frequency proton. According to [374].

proton frequency. Experimental formula

$$b(1.67–4.36)B(2.97)f(40–50) .$$

These data are presented in Fig. 2.24 in the form of amplitude dependences at different frequencies. The window structure of the response in frequency and amplitude of the magnetic field is clearly visible. A sharp "dip" in the center, just where the maximum effect is expected, confirms the data [551], although it does not yet have a reliable explanation.

Apparently, the proton is the only more or less reliable established target of the MP action, since the cyclotron frequency proton frequencies differ by an order of magnitude from those of other biologically active ones. significant ions.

Zinc

Thomas, Schroth, and Liebow [696] suggested that zinc ions may be involved in the behavioral response of rats to perpendicular constant and alternating magnetic fields. Blackman, Benan, and others [480] discussed the involvement of zinc ions in the reaction of calcium ions release from brain tissue under conditions combined MP.

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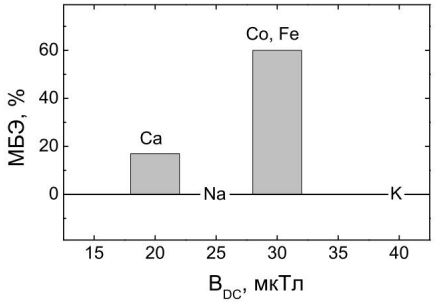


Fig. 2.25: Change in the rate of proliferation of neuroblast cells flippers in magnetic conditions, BAC = 20 ÿT, f = 16 Hz, and their correlation with cyclotron ion regimes, according to data [666].

In the work of the author, Belyaev and Alipov [303] the processes with participation of conformational rearrangements of the *E. coli* genome during an hour's exposure to an altered constant MP B(0–110 ± 1/1). Dependence The dependence of the viscosity of the lysed cell suspension on the magnitude of the constant field in which they were placed during exposure has a complex polyextreme form, Fig. 4.48. To explain the dependence, the mechanism of ionic interference was used, involving symbatically reacting calcium and zinc and oppositely reacting magnesium. This combination was unique, that is, no other biologically

important ions or their combinations did not give the same good agreement between the experimental and calculated curves. This indicates a possible contribution zinc ions in magnetoreception of *E. coli cells.*

Other elements

In [484] it was suggested that the statistically significant MBE of combined magnetic and electric fields that was observed at a frequency of 405 Hz at a constant MF BDC = 38 ÿT, are responsible carbon atoms 13C. For a given isotope, the NMR frequency in this field 406.9 Hz is close to the specified value. The natural content of this isotope in the biological system, 1.1%, is sufficient for its participation as a potential target of MP.

Smith, MacLeod and Liebow [666] investigated cell proliferation neuroblastoma N-18 in combined parallel MP

B(15–40/5)b(20)f(16).

They observed a 60% stimulation of proliferation in a constant field B(30). These conditions were noted by the authors as close to cyclotron conditions for Co ions: 30.7 ÿT and Fe2+ : 29.1 ÿT, Fig. 2.25.

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The effect of alternating magnetic field on sodium current in myocardial cells was shown by Piruzyan, Lazarev, and others in their work [57].

Microelements manganese, zinc, cobalt, vanadium, cesium, selenium, iodine, Molybdenum and copper are components of essential proteins that regulate the biochemical balance of organisms. Their quantities are small, on average from 10ÿ3 to 10ÿ6 %. However, a deficiency of microelements leads to serious illnesses. Therefore, these atoms, generally speaking, can also be targets of weak EMFs.

2.4 Correlation of biological processes with variations of GMP

The geomagnetic field (GMF) is characterized by the fact that both the constant and variable components of the field are equally important. On the one hand, the magnitude of the local GMF is constant with a good accuracy of ÿ 10ÿ2
time intervals of several days. In some experiments limited by this time, the constant component is significant.
Over large time intervals, on the order of months and years, the GMF experiences noticeable variations. Since the course of various biological processes
and slow variations in the GMF often correlate, then the fact of a change in the GMF is important. However, in this case, the GMF can be considered
quasi-static, in the sense that the time derivative of the GMF can be ignored in physical and mathematical models of the MBE. It is worth noting that physically justified criteria are still lacking.
frequencies at which a changing magnetic field should be considered constant with respect to biological effects. This is due to the lack of working MBE models, the analysis of which could provide such a criterion.

On the other hand, even on short time intervals, from a day and less, the GMF vector experiences variations that are insignificant in magnitude, but
also correlating with the course of certain biological processes.
Moreover, the time course of GMF variations is shorter than the characteristic times of the bioprocesses correlated with them. In this case, the variable component of the GMF should be considered more significant than the constant component.

Characteristics of the geomagnetic field, their relationship with the processes
The Sun has been described many times, see, for example, [67, 166, 224], and is reproduced here only in general terms. The GMF is close in shape to a dipole field, the axis of which is inclined to the Earth's rotation axis by 11.5o. The GMF strength decreases from the magnetic poles to the magnetic equator.

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approximately from 0.7 to 0.4 Oe, with the GMF vector in the northern hemisphere directed downwards. It is assumed that the GMF is a consequence of hydrodynamic flows of the Earth's liquid core.

Together with the solar wind, a supersonic flow of hydrogen ions flowing around the Earth, the magnetosphere forms the magnetosphere, a complex system of electromagnetic fields and charged particle flows. The magnetosphere is compressed by the solar wind on the dayside and strongly elongated on the nightside. Electrical processes in the magnetosphere create a variable component of the magnetosphere, no more than 10ÿ2 Oe over intervals of seconds. and more, excluding paleomagnetic periods. The Sun's own electromagnetic radiation is almost completely extinguished by the ionosphere, ionized layer of the Earth's atmosphere, with the exception of a narrow band from the near ultraviolet to the near infrared range. The solar corpuscular radiation that forms the solar wind is subject to random fluctuations due to flares in active regions on the Sun.

The Sun has its own magnetic field, which, unlike the geomagnetic field, is not like a dipole field. Solar wind streams capture the magnetic field from the Sun's surface and carry it toward Earth. In orbit
The Earth's field, called the interplanetary magnetic field, has a magnitude of only several nT and is directed either towards the Sun or away from it, thus forming a sectoral structure of the interplanetary magnetic field. Since the equatorial region of the Sun, with which its magnetic field is associated, rotates with period of about 27 days, then during this time on Earth one can observe Several times, the sectors of the interplanetary magnetic field change, that is, the direction of the field changes. Usually, the number of sectors is even, naturally, and does not exceed four.

The Earth passes the sector boundary in a few minutes. After that significant changes in the magnetosphere may occur. If the projection of the interplanetary magnetic field onto the Earth's rotation axis is directed from the north to the south (Bz < 0), then the interplanetary and geomagnetic fields are significantly parts of the magnetosphere compensate each other. This leads to more deep and uneven penetration of the solar wind into the magnetosphere causes increased electromagnetic disturbances on the Earth le.

Conventionally, variations in the GMF are divided into calm and disturbed. Calm variations are caused by the diurnal and seasonal motion of the Earth, as well as the motion of the Moon, include the effects of the sector structure of the interplanetary magnetic field. Quiet diurnal variations of the GMF usually do not exceed 60–70 nT. Disturbed variations are quasi-periodic

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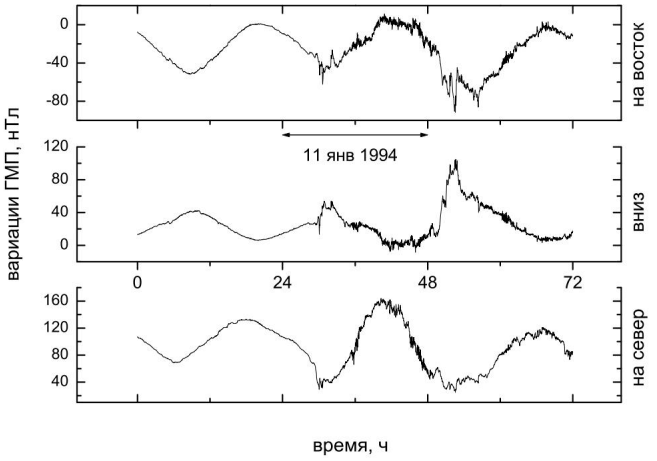


Fig. 2.26: Variations of various components of the geomagnetic field according to geostationary satellite data, January 10–13, 1994. Measurements were taken at one-minute intervals. Diurnal variations in the components and geomagnetic disturbances from 6:00 a.m. on January 11 are clearly visible.

Magnetic storms, irregular and irregular pulsations lasting from fractions of a second to minutes, are caused by random processes on the Sun that affect the magnetosphere through the solar wind. Therefore, disturbed variations occur approximately four days after solar "cataclysms." This is the time during which the ions
hydrogen from the Sun reaches the Earth. Disturbed variations reach quantities of the order of 1 ÿT and durations from hours to days.

Fig. 2.26 shows a record of variations in the GMF components made from a geostationary space satellite, //.
The satellite revolved with the Earth at an altitude of several radii
The lands are above a certain meridian, so that its earthly coordinates remained almost unchanged for a long time. In the figure
Both calm and disturbed variations are visible. It is the latter
correlate with the state of the biosphere. To see in more detail
the nature of these disturbances, that is, how to isolate the “useful signal”, carry out processing of such data.

Fig. 2.27 shows the result of the sequential procedure
differentiation, squaring and sliding (15 min)

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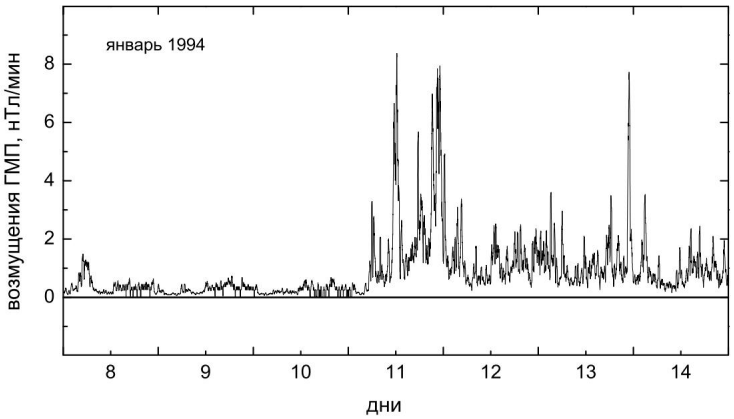


Fig. 2.27: Perturbations of the rate of change of the GMF module during geomagnetic storm. Processing of one-minute measurements of the geomagnetic field Bn,8–14.01.1994.

averaging similar data for the modulus of the GMF vector over the interval in several days, including the interval Fig. 2.26. The absolute rate of change of the GMF is shown, or more precisely, the course of its standard deviation. The curve is formed by points

$$\left(\frac{\ddot{y}B}{\ddot{y}t}\right)_n = \frac{1}{tN}\sum_{i=n}^{n+N}(Bi\ \ddot{y}\ Bi+1)^2)^{\frac{1}{2}}, \qquad t = 1\ \text{min}, N = 15\ .$$

It is clear that relatively quiet days alternate with days with pronounced disturbances in the rate of change of the GMF. It is still unclear which of the two factors, the disturbance of the field or the disturbance of the rate of change of the field, is more closely associated with the course of biological processes.
processes.

Thus, the GMP can be in various states, characterized by the presence or absence of certain variations and
distribution of their intensities.

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2.4.1 Parameters and indices of geomagnetic activity th field

To describe the state of the variable component of the GMF, use various local and global indices of geomagnetic activity.
To determine the indices, *the parameters of the GMF are essential,* which set the magnitude and direction of the GMF vector depending on the location, where it is measured. Let's note the following parameters.
H is the horizontal component of the GMF vector,
Z is the vertical component of the GMF vector,
I is the inclination or magnetic declination, the angle between H and the vector GMP,
D is the declination, the angle between the vector H and the direction of the geographic meridian at a given point, from north to south.

The nature of these values' variations over time determines various indices of geomagnetic activity. The meaning of some commonly encountered indices is given below.

C-index. Determined over a daily period. Takes values 0, 1 or 2 depending on the assessment whether the given day was in relation to magnetic activity as calm, disturbed, or strongly disturbed.7

u-index. It is defined as the difference between the average values of the module H for data and the previous day.

K-index. It is determined every three hours as an estimate of the average st-indignation on a ten-point scale.

Ci is the average value of the C-index for several major observatories located in different parts of the planet.

Kp is a special averaging of K-indices from various observatories. The sum of Kp-indices over a day reflects the average intensity solar wind disturbances.

Ap is the average amplitude of voltage fluctuations over a day GMF at mid-latitudes.

AE is a measure of geomagnetic activity in high and Dst in low latitudes. Determined for different time intervals.

There are also many other indices that reflect various frequency-temporal, spatial and power characteristics of the complex process of changing the GMF [166, 90].

7There are many criteria for such an assessment; their precise description does not exist. specifically for the purposes of this book.

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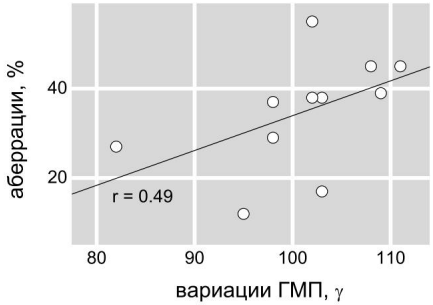


Fig. 2.28: Correlation diagram. Variation of the horizontal component of GMF and change in the frequency of chromosomal aberrations in rat liver cells.

Data processing Fig.34, [377].

2.4.2 Characteristic experimental data

Correlations in the time course of various indices of geomagnetic activity have been observed with a variety of biological characteristics and processes. Since such correlations arise already in
at the cellular level and even at the level of chemical reactions *in vitro,* for example in the Piccardi reaction, then, naturally, it is difficult to find the process in
biosphere, which would *not correlate* with one or another parameter
heliogeosphere.

In many frequency ranges, starting from approximately 0.1 Hz and
Below, a correlation of GMF variations with certain biological processes was discovered. Pioneering scientific work in this area was carried out by Chizhevsky and Piccardi. Their works, see, for example, [212, 160], served as a dramatic foundation for the further development of heliobiology. It took almost half a century for the study of helio-geo-biocorrelations to transform from a “pseudoscience” first into an exotic [52], and then into an ordinary scientific direction

[216] Now it is becoming one of the most urgent and priority-
nykh.

Dubrov's extensive monograph [377] is devoted to the study
Correlations of biospheric processes, from plant cells and microorganisms to higher animals, humans, and ecological systems, with variations in the geomagnetic field over a wide range of time scales from hours to decades. The book contains over 1,200 references to original works.
domestic and foreign researchers. Based on the comparison
geophysical and biomedical data, for the first time it has been convincingly shown that bio-GMP correlations are not an exotic phenomenon,
and a widespread fact deserving careful study. Below are the correlations found in [377] demonstrating the connection
geomagnetic variations and some life processes, mu-

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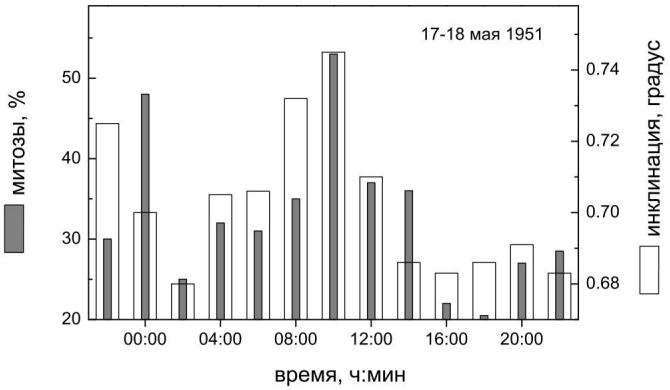


Fig. 2.29: Dynamics of the daily rhythm of cancer cell mitosis and variations in the geomagnetic field inclination, according to Fig. 32 from the monograph [377].

tations, cancer, etc.

Figure 2.28 shows the data from a regression analysis of the approximately synchronous time course of two processes. One of them is this is a change in the frequency of chromosomal structural defects in cells rat liver after administration of the antitumor drug dipin. The second process is a change in the magnitude of the horizontal component of the GMF at the location of the experiment. Figure 2.29 shows the circadian Mitotic rhythm of human carcinoma cells and the significance of GMF inclination at the appropriate time intervals. Figure 2.30 shows the seasonal the course of chromosomal inversions of the ST gene *in Drosophila* under natural conditions and average monthly changes in inclination.

The correlation diagrams for these graphs are shown in Fig. 2.31, Fig. 2.32. As can be seen from these graphs, the correlation links are present on different time scales, which speaks in favor of the hypothesis about the direct influence of GMF variations on the course of biological processes.

In [100] acceleration and deceleration of the development of some plants when the Earth passes through sectors with positive and negative polarity of the interplanetary magnetic field, respectively. [6] a connection between the biorhythms of aquatic activity and changes in regional MP is shown. The bioluminescence of bacteria changes significantly *Photobacterium* during magnetic storms [29], and changes in the

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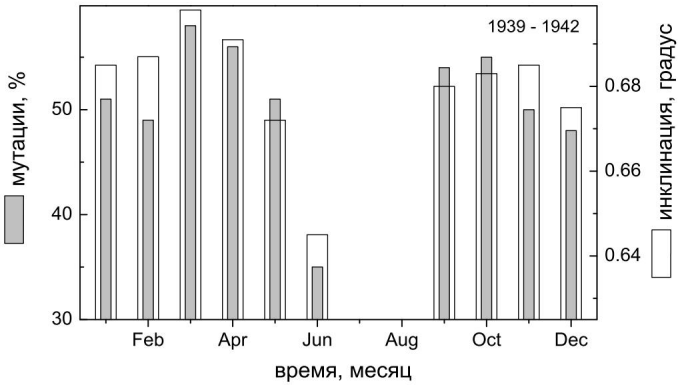


Fig. 2.30: Dynamics of the natural seasonal mutation process and variations in the GMF parameter, according to Fig.65 from the monograph [377].

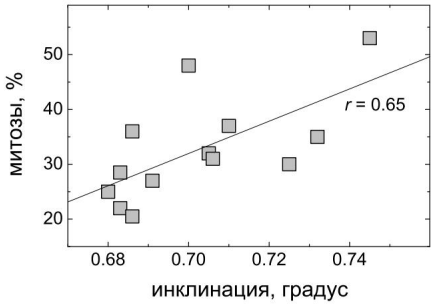


Fig. 2.31: Correlation diagram of biological and geomagnetic processes in Fig. 2.29.

begin a day or two before the storm begins and continue for two or three days days after the storm subsided.

Gurfinkel, Lyubimov et al. [44] conducted regular measurements of capillary blood flow in 80 patients with coronary heart disease.
A deterioration in capillary blood flow on the day of the magnetic storm was observed in 60–70% of patients. At the same time, only 20–30% patients responded to changes in atmospheric pressure.

Oraevsky, Golyshev, and others [155] showed that even short-term variations in the polarity of the interplanetary magnetic field during the day correlate with serious medical pathologies. Figure 2.33 shows a regression analysis of their data. A significant correlation exists between the number of ambulance calls for heart attacks myocardium (on days with an abnormally large or abnormally small number

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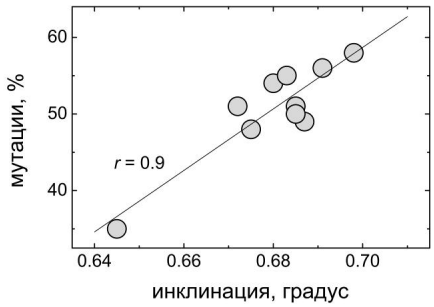


Fig. 2.32: Correlation diagram of biological and geomagnetic processes in Fig. 2.30.

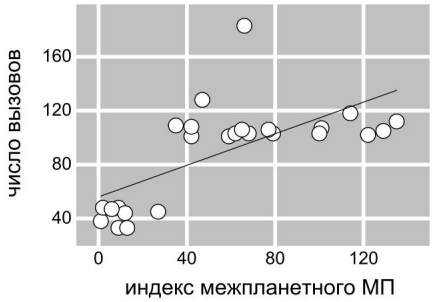


Fig. 2.33: Number correlation ambulance calls for myocardial infarction, processing data [155], and the interplanetary magnetic field index.

calls) and the index of variations of the interplanetary magnetic field. The index approximately corresponded to the integral value of Bz over a day, that is, the z-component of the interplanetary magnetic field. It was calculated as the sum of hourly values of the quantity

$$Bs = \begin{matrix} 0, Bz \ddot{y} 0 \\ \ddot{y}Bz, Bz < 0 \end{matrix}$$

for a 24-hour time interval, shifted back by 6 hours in relation to the days under study. The authors obtained similar statistics for calls regarding stroke, hypertensive crisis, bronchial asthma, epilepsy and various injuries.

A detailed statistical analysis of the relationship between the frequency of acute cardiovascular pathologies during 1979–1981 and variations in the GMF was carried out by Villoresi, Breus et al. in [45]. The authors showed that strong geomagnetic storms on a planetary scale are associated with an increase in the number myocardial infarctions by 13% with a statistical significance of 9ÿ and the number of cerebral strokes by 7% with a statistical significance of 4.5ÿ. It was found that such pathologies as myocardial infarction, angina pectoris and cardiac arrhythmias are approximately similar in

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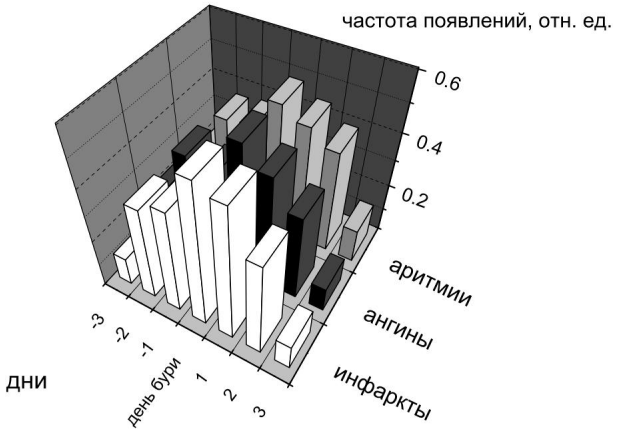


Fig. 2.34: Relative frequency of cardiovascular pathologies before, during and after magnetic storms, according to the work [69].

simultaneously correlate with the occurrence of geomagnetic storms [69]. Fig. 2.34 presents this data.

A review of the work and original data on the correlation of cardiovascular exacerbations and transport accidents with geomagnetic activity is given in the article by Ptitsyna, Villoresi et al. [87].

Based on 9-year observations, in [93] a correlation was found between geomagnetic activity, the Ap index, and the density of true predictions in mass numerical lotteries, R = ÿ0.125 with a significance 99.74%. Density correlated with Ap precisely on the day of the draw and did not cor-correlated with this index in previous or subsequent days.

It has also been reported that geomagnetic disturbances correlate with a decrease in the analgesic effect of morphine in mice [592], KPK index (short-period oscillations of the H-component of the GMF) and the functional state of the brain [104], the change in the direction of the interplanetary magnetic field and the content of leukocytes and hemoglobin in the blood of mice [172], Daily sum of K-indices and suicide rate [43], Ap-index and criminal activity in Moscow [81], the Ap-index and money supply in circulation in Russia [211], the presence of magnetic storms and the probability aviation accidents and disasters [137].

More detailed information about the various biospheric processes

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data correlating with geomagnetic activity can be found in special issues of the journal *Biophysics* [133, 134, 135], in collections [52, 53, 223, 183] and others.

2.4.3 Ideas about the physical nature of bio-GMP correlates tions

The mechanisms that ensure the correlation of the course of biological processes with variations in the GMF are still unclear. There are several points views on the possible physical nature of this phenomenon.

Direct action of the magnetic field

The most common view is that variations in GMP have a direct effect on biological or biochemical *in vivo* processes [40, 377, 93, 189, 44, 31, 6]. This, in particular, determines the question [41] is whether heliobiology can be considered a section of electromagnetic biology.

There is empirical evidence both for and against this idea. Cycle research by Opalinskaya and Agulova [149] on the effects of artificial variables of the MP, of the order of GMP fluctuations and more, confirms validity of the idea. At the same time, not all data from this group are confirmed in independent studies [161].

Agadzhanyan and Vlasova modeled in [1] short-period pulsations of the GMF with frequencies of 0.05–5 Hz and an intensity of about 100 nT. They found that such MPs have an activating effect on spontaneous rhythmic activity of nerve cells in the mouse cerebellum.

Kashulin and Pershakov report that artificial magnetic pulsations that imitate the level and time course of local magnetospheric pulsations stimulated the growth of some cereal plants [105]. At the same time, stronger variations

the fields did not produce a biological response, which confirms the hypothesis direct action of GMF variations on biosystems.

According to Tyasto, Ptitsyna and others [55] on weekends and holidays days, a 40–50% decrease in magnetic fluctuations of man-made origin in the frequency band of ÿ 10ÿ3–10ÿ1 Hz is observed and, at the same time, a significant 70% decrease in the number of myocardial infarctions. According to the authors, this indicates that magnetic fluctuations can serve as a trigger for acute pathologies in people with cardiovascular diseases.

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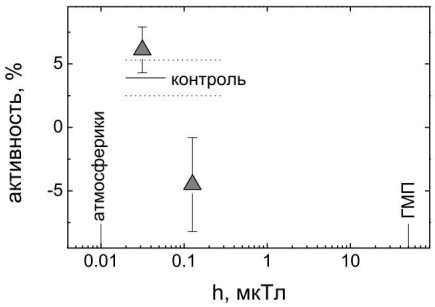


Fig. 2.35: Proliferative activity of glioma cells in EMF, simulating natural atmospheres depending on the pulse amplitude, according to data [250].

Rachenstroth-Bauer, Hoffmann et al. [250] investigated the proliferative activity of C6 glioma cells *in vitro* when exposed to EMF.
simulating natural atmospherics, short, weak, rapidly decaying electromagnetic field pulses. A frequently observed form of magnetic field pulse
atmospherics, in the form of a wave packet with a length of ÿ 400 ÿs, frequency ÿ 10 kHz, 5–20 kHz bandwidth, and ÿ 0.01 ÿT amplitude were digitized and entered into the PC memory. Then, using a computer, a series of such pulses were generated, separated by a random interval of 50–
150 ms, amplified and fed to a single-turn pair of Helmholtz coils. The pulse amplitude was varied. The constant magnetic field level,
apparently corresponded to the local GMF. Exposure during
24 hours of this regimen caused a change in proliferative activity (Fig. 2.35), measured by radioactivity per unit amount of DNA with 3H-thymidine. Thus, combined magnetic resonances with a noise-like variable component possess biological activity. Moreover, the dependence on a relatively small amplitude and

is non-monotonic in nature here. These data also confirm
hypothesis of the direct impact of GMF disturbances on the biosphere.

The possible biophysical mechanisms of the direct action of such small-amplitude magnetic field disturbances are currently far from understood. The mechanisms of the biological action of fields seem more certain.
order of the Earth's field, that is, three to four orders of magnitude larger, but even for them, the corresponding mechanisms should be considered as assumptions requiring further study.

Radon hypothesis

An alternative view on the nature of bio-GMP correlation is related to the dependence or correlation of radon concentration in ground-level
layer of the atmosphere and electromagnetic activity on the Earth's surface

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[213].

Radon isotopes, mainly 222Rn, are constantly released from the soil in small concentrations as a result of the alpha decay chain of small amounts of 238U, 235U naturally present in the lithosphere.
and 232Th. Radon is a chemically neutral heavy
an atomic gas with a half-life of 1600 years. The natural level of radiation in the biosphere is approximately half due to the decay of radon and its short-lived derivatives 218,216,214Po, 214Bi,
214,212Pb. Radiation levels are subject to strong variations, by tens of times, due to mechanical processes in the lithosphere and "locking"
radon in the soil by layers of sedimentary water.

A significant correlation between the level of ground radiation and geomagnetic activity allowed Shem'i-Zade [213] to suggest a mechanism bio-GMF correlations. According to this hypothesis, bursts of geomagnetic disturbances lead to magnetostrictive deformation of minerals
and rocks containing ferromagnetic compounds. As a result,
the diffusion of radon from the soil increases and its concentration rises in the surface layer of the atmosphere. Due to respiration or metabolism, radon quickly penetrates into living systems, where changes in its concentrations cause a variety of biological effects. It should be noted that there are no known experiments with artificial magnetic fields that would confirm the striction mechanism in the lithosphere at such
small disturbances of the magnetic field, such as geomagnetic storms.

This issue is being discussed not only in connection with geomagnetic disturbances. Radon has been established as a risk factor for lung cancer. Radon decay products, in particular
Unstable polonium is carried by particles of various aerosols, which are always present in the air. Because they carry an electric charge, they are drawn to areas of increased electric field strength.

Henshaw, Ross et al. [425] measured the concentration of radioactive aerosols near electrical wires of household appliances using an alpha-particle sensor and found that it was increased several times. The authors raise the question of whether the presence of an electric field background of industrial frequency in residential and industrial premises leads to
near power lines, to excessive deposition of radon products on the surface of the lungs and further to cancer. Despite
small amount of experimental material, insufficient statistics, lack of special epidemiological and even biological
studies, the authors claim that they have found the missing link in

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physical mechanism of the connection between weak electromagnetic fields and risk cancer. According to their hypothesis, which has caused controversy and not shared by everyone, electromagnetic fields affect living things indirectly, through an increase in the concentration of radon products.

At the same time, in the work [2] no influence on the concentration of radon decay products from the much larger electric field of computer video terminals, reaching 30–
50 kV/m at a distance of 10 cm. In both the experiment and the control it was about 91.5 ± 2.5 Bq/m3.

General synchronization factor

Finally, a third look at the physical nature of the bio-GMP correlation takes into account the following circumstance. It is well known that the intensity of almost all biological and biochemical processes *in vivo* experiences cyclical fluctuations to one degree or another.
some of these biological rhythms, an obvious example being the circadian rhythm, is carried out to a certain extent synchronously with geophysical and even cosmophysical processes [160, 212, 377, 216, 112].
Infradian rhythms, around 3.5, 7, 27 days, are a consequence of the periodic activity and rotation of the Sun. These same rhythms are found in many biological systems, [31], including unicellular
accurate.

The Earth's rotation around its axis and around the Sun, and the movement of the Moon, drive certain biological rhythms. Variations in some GMF parameters are also associated with these processes. For example, the power spectrum of variations in the geomagnetic aa index is clearly
groups of spectral peaks were identified in the region of 27, 14, 9 and 7 days.
On the one hand, these rhythms are caused by changes in the solar wind parameters, on the other hand, they also manifest themselves in biospheric processes. Therefore, the correlation between the time course of biological processes and the GMF is not means their cause-and-effect relationship, which has been repeatedly noted in the literature. It is possible that variations in GMF are not the cause causing the biological response. They may be a consequence
unknown true cause, general synchronizing natural
factor.

Variations in environmental parameters are often synchronous, since are largely due to solar universal rhythms [42]. Electromagnetic disturbances are accompanied by increased infrasound noise, microseisms, while the intensity decreases
galactic cosmic rays and the radioactivity of the atmosphere increases

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spheres. This conjugacy in the change of geophysical fields, as noted by Vladimirsky, Narmansky and Temuryants, complicates the answer to the question is what physical factor is the main cause the emergence of biorhythms.

The average amplitude of fluctuations of processes of various natures, reports Shnol in his work [217], undergoes noticeable changes already 1–2 days before the Earth crosses the boundaries of the interplanetary magnetic field sectors. This rather suggests that there is an unknown influencing factor, possibly related to processes on the Sun. In work [4] it is suggested that this factor is the torsion fields of cosmic bodies. The authors [112] note that it has a high penetrating ability, correlates with biological and geomagnetic activity, with the flux of radio emission from the Sun in the meter and centimeter ranges.

This also confirms the hypothesis of the “non-magnetic” nature of bio-GMF. correlations.

The question of the impact on living organisms remains little studied. weak low-frequency electric fields against the background of a constant magnetic field. A brief review of research in this area is available in the work of the author and Goldman [304]. It is known that the vertical component of the electric field of geomagnetic pulsations reaches 10 V/m and is in fairly strong correlation (r ÿ 0.8) with variations in the meridional components of the horizontal component of the GMF [210]. Therefore, it is impossible to exclude the possibility that the biological effect is not exerted by the geomagnets themselves nitary variations, and geoelectric fields synchronous with them.

There are probably several generally equal mechanisms, providing the correlation under discussion. Their competition, depending on many difficult-to-take-into-account factors, leads to not very large correlation values and low reproducibility results. At the same time, the very diversity and multiplicity of manifestations of bio-GMP correlations indicate its non-random nature.

2.5 Spin effects in magnetobiology

Information on the manifestation of spin degrees of freedom in magnetobiological experiments is extremely scarce. At present, there are no experiments reproduced by different research groups. This state of affairs is likely due to the traditionally large magnitude MF used to observe spin effects. In general, the signal-to-noise ratio in a series of similar experiments increases proportionally to the MF. Another reason holding back the development of the spin-

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of the new effects in magnetobiology, there remains a small amount of magnetic energy spin moment of the electron, not to mention the nuclear moments, in MP order of magnitude of the geomagnetic one. It is only 10ÿ7 ÿT, which , therefore, the IBE many consider impossible for physical reasons.

At first glance, it seems unlikely that the nuclear spins of the atoms of living tissue molecules can influence life processes. After all, nuclear spins interact with the environment through the interactions of the magnetic spin moment with internal non-uniform electric and magnetic fields. These magnetic interactions are proportional to the nuclear magnetic moment, which is twofold

order of magnitude smaller than the electron one. Nevertheless, nuclear spins are somehow involved in biochemical reactions. Indirect evidence of this is provided by the fact that the fact that various substrates of biological systems, cells, tissues have different carbon isotopic compositions [362]. In [96] it is reported that that the reaction of pyruvate decarboxylation is associated with the separation of carbon isotopes 12C and 13C, and the mechanism of the occurrence of isotopic heterogeneity in amino acids is not entirely clear. Dependent on this reactions, the isotopic composition of carbon in carbon dioxide exhaled by humans and animals undergoes daily variations [448] and reflects hormonal and metabolic status [186]. The ratio of carbon isotopes in exhaled air can change over the course of several minutes after taking certain medications. This is convenient for quick diagnostics. In laser orthomolecular medical diagnostics [184] The 13C/12C ratio is used to judge the presence of certain diseases of the digestive system.

The two isotopes differ in mass by 8%, while 13C, unlike 12C has spin, that is, it has a different physical quality. It is possible The spin of 13C, not the mass difference, is the factor that determines separation of isotopes in relevant biochemical reactions. Especially In this sense, the observation of the isotope effect for relatively heavy ions of Ca, Zn, Cu, etc. is attractive; the mass difference isotopes here make up only 1–2%. There is indirect evidence of the involvement of hydrogen nuclear spins in biochemical processes. in the work of Lobyshev, Tverdislov et al. [234], where they observed activation membrane potassium-sodium pump with a small admixture of heavy water D2O.

Apparently, the MBE by the mechanism of spin resonance in its usual sense, as a resonant change in the rate of energy absorption EMF relaxing spin system is really unlikely

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are. Including the unlikely mechanisms of MBE associated with the accumulation of energy of the spin magnetic moment. However, it is possible and necessary argue with the thesis that magnetic interactions of electron and nuclear spins are irrelevant to magnetobiology. The question of the role of spins, including nuclear ones, as mediators in the transmission of information MP signals remain open [26].

There is a known point of view according to which the mechanism of biological action of low-frequency magnetic fields is based on the magnetosensitive process of recombination of free radicals present in biological tissue. This process depends on the state of the electronic spins of the radicals entering into the reaction. The state of the spins, in turn, In turn, it depends on the magnetic field. However, there is no reliable experimental data confirming such a mechanism of magnetoreception. This is mainly due to the fact that it does not have the property of frequency selectivity and is sensitive only to the absolute value of the magnetic field. The fact of magnetoreception in itself, therefore, does not necessarily indicate spins are involved, there are other explanations for the MBE that are not spin-related. Therefore, experiments in which spins are involved are collected below. manifest themselves in frequency-selective biological responses to alternating electromagnetic field, with effective frequencies near the spin frequencies resonances. Such experiments, if not considered artifacts, directly indicate the involvement of spin processes in magnetoreception.

Jafari-Asl, Solanki et al. [370] performed one of the the first works where the features of biological effects were compared with spin magnetic resonance conditions. Yeast cells were studied by dielectrophoresis, cell displacement in a non-uniform an electric field due to their polarization. Pre-treated *Saccharomyces cerevisiae* cells were placed in an electrochemical cell under a microscope. After the field was turned on, the cells began to move toward the electrodes and formed elongated chains on them. along the field lines. After 3 min, the electric field was switched off and the average length of the chains was measured. The experiments were carried out in an adjustable constant magnetic field B(50–500) and an alternating electric field f(200–5 104), the potential difference between the electrodes was 40 V. The authors The cell design was not reported, so it is difficult to estimate the magnitude of the electric field and its gradient. There was also no data on mutual orientation of electric and magnetic fields.

Fig. 2.36 shows the experimental curve, the result of processing five frequency spectra obtained in MP 50, 100, 150, 300, 500 ÿT. The curve shows a distinct dip in the region

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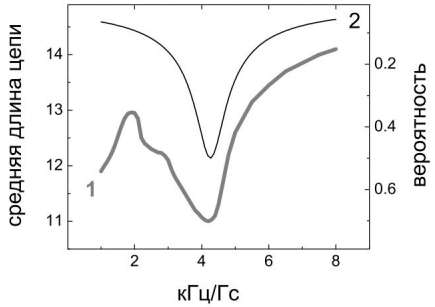


Fig. 2.36: Comparison of experimental data [370] on dielectrophoresis of yeast cells in a weak magnetic field (1) with the 1H NMR resonance curve (2).

4.26 kHz/G. The dependence of the probability amplitude of one of the spin states of the Zeeman doublet, calculated using the proton NMR mechanism under the condition bp/B = 0.1, is also shown.

Since the experiment used an alternating electric field, rather than a magnetic field, the results of Fig. 2.36 serve only as an indirect indication of the possible role of proton nuclear spins in these
experiments.

The work also presented the spectra of complex permittivity (f)= (f)+ i(f) in the range f(90–105),
and in the frequency range corresponding to the electron spin resonance in MP 50 ÿT for cell culture with a concentration of 1.9 · 106 mlÿ1. At at some fixed frequency values, narrow bands, ÿ 1 Hz, were observed, bursts of 3–15%. Below are the frequencies, in Hz, found
in the experiment, the nuclei that, according to the authors, correspond to them, and the NMR frequencies of these nuclei in a field of 50 ÿT

2130	1H 2128.2
861	31P 862.6
563	23Na 563.4
208	35Cl 208.8
99	39K 99.4

There is almost complete agreement within the experimental accuracy (~1 Hz). An increase in dielectric losses at frequency is also indicated.
electron spin resonance ÿ 2.79 MHz/G.

The same work reports on the study of other cells under NMR conditions. Cultures of soil bacteria were exposed to magnetic fields under 1H NMR conditions.

B(25 103)Bp(85)f(1.064 106) .

The concentration of cells in the experiment increased twofold compared to the control after 10 hours of exposure; the size of the smallest ones was halved

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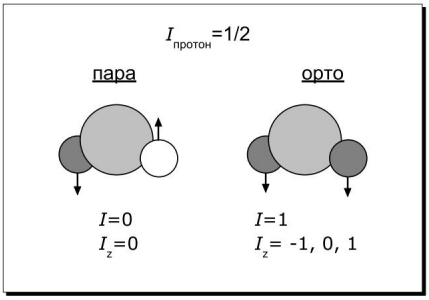


Fig. 2.37: Para- and ortho- states of the water molecule. Ortho-states have symmetrical
we by the permutation of spins by wave functions.

cells. It was possible to stop the reaction of the enzyme lysozyme with its substrate under conditions close to 1H NMR

B(2 105)f(7 106–107) .

Similar data are presented by Shaya and Smith in [660]. The authors [370] conclude that their data indicate the ability of 1H NMR conditions speed up the process of DNA replication.

Reduction in the average lifespan of *E. coli* cell generation in under proton magnetic resonance conditions (perpendicular fields) was shown by Aarholt, Jaberansari et al. in [587]. They also reported that 55 MHz EMF with a bandwidth of 50 Hz caused the formation of cataracts in the eye pupil of animals *in vitro* if the modulation frequency corresponded to 1H NMR, i.e., 2.13 kHz in the geomagnetic field
50 ÿT.

The works of Konyukhov et al. [116, 115, 150] contain indirect evidence that nuclear spins of protons can participate in the processes of primary reception of magnetic fields by biological systems. The authors report that
they succeeded in discovering *the existence* of liquid water with a metastable deviation from the equilibrium ratio, 3:1, of the amounts of ortho- and para- molecules of water H2O. In the singlet para- state, the molecular spin I = 0 is formed by oppositely directed spins
protons and has a unique projection Iz = 0 onto an arbitrary axis quantization, Fig. 2.37.

In the ortho state, the proton spins are unidirectional, and the molecular spin I = 1 has three possible projections Iz = ÿ1, 0, 1
and forms a triplet in a magnetic field. In a strong external magnetic field, the energy its interactions with proton magnetic moments, ÿH, are greater
energy of magnetic dipole-dipole interaction ÿ ÿ2/r3. This is

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takes place in the field

H> ÿ 10ÿ6 r3 ,

Then the proton spins behave almost independently of each other. In a weak magnetic field, the proton spins form a molecular spin, which interacts with the magnetic field as a whole.

The process of adsorption of water molecules from the gas phase is sensitive to rotational state of water molecules and, therefore, reveals the molecular spin state. In a special weak NMR 1H resonance MP

B(150)Bp(5)f(ÿ 6384) ,

providing quantum transitions between states Iz = 0, Iz = ±1, it was possible to register an increase in the adsorption rate of ortho-molecules water [116] and, further, on this basis, to obtain liquid water with a nonequilibrium content of ortho- and para-molecules. The authors called it spin-modified water. Using submillimeter spectroscopy methods
It was found that the lifetime of spin-modified water is 45 minutes at room temperature and 4.5 months at liquid nitrogen temperature. Biological activity of spin-modified water is assumed.

The physical mechanisms that lead to such a long lifetime of nuclear spin degrees of freedom in liquid water remain unclear. This may be due to the peculiarities of proton exchange in liquid water in magnetic fields [27, 23]. However, the very existence of such states at room temperature indicates their potential significance in biology.

In [484] the MBE observed under the conditions B(38)b(?)e(?)f(405) was associated with the NMR of carbon 13C , the frequency of which in the indicated MP is 406.9Hz.

Direct change of biosystem parameters in a weak magnetic field at the 1H NMR frequency was observed by Lednev, Srebnitskaya et al. in [179]. The found dependence of the MBE in the cells of regenerating planarian neoblasts on frequency had the form of a resonance, Fig. 4.33. However, the MBE spectrum filmed with parallel orientation of magnetic fields

B(42.74 ± 0.01)b(78.6 ± 0.8)f(1808–1830/ ÿ 3) .

With this orientation, NMR does not exist, which indicates a different, associated with the proton spin, a physical mechanism of the MBE. One of such mechanisms was discussed in [292, 293].

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Ossenkopp, Cavaliers et al. [432] observed a change in the analgesic effect of morphine in mice in the MR operating according to a standard MRI protocol. It is not yet clear whether this effect is related with excitation of the spin subsystem, or the active principle was a strong constant MP of the tomograph itself. In any case In this case, these facts point to possible unpredictable consequences of the widespread procedure of MRI scanning of humans.

2.6 Effects of low-frequency electric fields

The biological effect of an electric field is primarily due to the ionic currents it causes in the intra- and extracellular plasma. The redistribution of ions leads to local changes.
electrical potentials on the surface of macromolecules and cellular membranes. This, in turn, is accompanied by changes in the rates of biochemical reactions.

It is known that relatively intense and short pulses electric current facilitates the penetration of large molecules type of DNA and proteins into biological cells. For example, the anticancer efficacy of bleomycin is limited by the fact that the molecule Bleomycin is unable to penetrate the cell membrane. Current pulses increase membrane permeability and lead to the corresponding biological effects. The ability to act relatively does not cause strong constant and alternating electric fields doubts, although in this case the mechanisms of such action are not always defined [314].

In [399], human skin fibroblast cells were exposed to electric field of 60 Hz with a strength of 100 kV/m and did not find changes in the rate of cell growth and DNA repair. Also, no changes were observed in the properties of cancer cells after exposure to electric fields, in contrast to the case of combined irradiation with magnetic fields [601]. A brief summary of studies on the biological effects of electric fields with a strength of 5–105 kV/m is available in [679].

Serpers and Tsong [658] established that alternating electric field affects the work of (Na,K)ATPase on the membranes of human red blood cells. They placed a suspension of red blood cells enriched with the isotope rubidium 86Rb between electrodes and measured the uptake of radioactive labeled with red blood cells after an hour of exposure. It turned out that the rate

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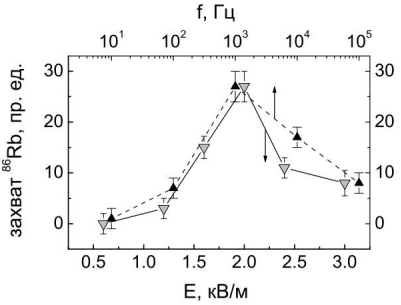


Fig. 2.38: Capture of rubidium label during sus-
variable red blood cell counts
electric field, frequency-
amplitude dependencies.

passage of rubidium ions, which, due to their similar size, are
replace potassium in the operation of the membrane pump, depends on extreme way, both from the frequency and from the amplitude of the field. The same exposure did not affect the passage of Na ions measured by the 22Na label. Data are shown in Fig. 2.38 and demonstrate a fairly wide “resonance” in frequency with a center near one kilohertz. The authors note that This corresponds to the frequency of the protein's own biochemical conformational changes—the so-called kinetic resonance is probable. Decline
The effect with increasing field amplitude is explained by the field-induced change in the geometry of the protein, which leads to disruption of its normal functioning.

2.6.1 Weak electric fields

It has been established that in a number of cases, weak electric fields induced by low-frequency magnetic fields lead to biological effects.
Correlation between the level of the induced electric field and
A biological effect was observed, for example, by Schimmelpfeng and Dertinger in [652]. Cell proliferation (HL-60) was studied in a sinusoidal 2.8 mT 50 Hz MF. A uniform MF affected cells only where the induced electric field exceeded the threshold
level 4–8 mV/m.

A review of experiments that revealed the effectiveness of electrical stimulation of cellular metabolism was compiled by Berg [281]. Changes in the synthesis of biopolymers, enzyme activity,
membrane transport, proliferation and morphological structures.
These changes occurred under the influence, in particular, of low-frequency variable magnetic fields of the 0.1–10 mT level, which generate electric fields of the above-mentioned level in the biological environment. In some cases, frequency and amplitude changes were detected in this range.

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windows of stimulation efficiency [520]. Analysis of experiments at
stimulation of the mT range of MP, in the absence of detailed amplitude-frequency
spectra, is complicated due to the possible involvement
mechanisms of different nature, for example, spin and electrochemical, in the formation of
the final response. Therefore, for the study of the biological effects of an electric field, it is
preferable to use an electric field rather than a magnetic field. Although here, too, outside of
a detailed study, it remains unclear what the electric field as such is

or electric current (electrochemical processes) causes
final biological response.

In some cases, the current induced by the electric field,
is small. At the same time, the electric field itself can have a magnitude comparable
in the atomic effects caused by a weak magnetic field (see sections 1.4, 4.6). Then
the biological effect of the electric field could be considered from the same
standpoint as
MBE. The similarity of the biological effects of low-frequency MF and electric fields,
the correlation of their effective parameters, were discussed by Blank and
Goodman in the work [322]. The difficulty here is that
it is not clear in advance what kind of situation is being dealt with in the experiment,
when relatively small non-thermal electric fields are used:
with the electrochemical action of the current or with the action of the field itself.
Therefore, the choice of experiments discussed below is to some extent
subjective.

Bowen and Adie [266] found frequency and amplitude windows at
the effect of a low-frequency electric field on the flow velocity
calcium ions 45Ca from chicken brain tissue, Fig. 2.39. The maximum effect was
in the region of 16 Hz and 10–60 V/m. Field strengths are indicated
between the plates of a capacitor in which tissue samples were placed.
The electric field inside the tissue is reduced due to the dielectric
polarizability of the molecules of the medium and due to the redistribution of carriers
charge, in this case ions.

Interestingly, the opposite effect of increasing the outflow velocity
calcium was observed by Bowen, Kaczmarek and Adie [268] under conditions of
irradiation with a modulated high-frequency EMF of 147 MHz. Moreover, the window
efficiency near the frequency of 16 Hz was recorded during scanning
modulation frequencies in the low-frequency range.

MacLeod, Lee and Ehrlich investigated in [565] the entry of 3H-proline into newly
synthesized collagen in the collagen matrix of bovine fibroblast cells. They found
that a weak, 0.1–100 ÿA/cm2, low-frequency electric current, applied for 12 hours,
slowed the entry

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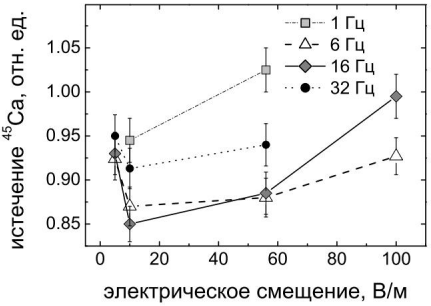


Fig. 2.39: Frequency and amplitude windows under action electric field on the outflow calcium ions, preliminarily introduced into the brain tissue, data [266].

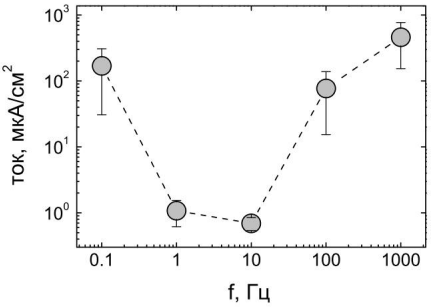


Fig. 2.40: Amplitude of the threshold current density, reducing the rate of protein synthesis in fibroblasts in an electric field, according to data [565].

proline, starting from a certain threshold level, and the value of horn depended on the field frequency, Fig. 2.40. Maximum 30% response was achieved at a frequency of 10 Hz and a current density amplitude of 0.7 ÿA/cm2. Since the tissue resistivity was about 65 Ohm cm, the authors concluded that alternating electric fields of the order of 4.5 mV/m are capable of eliciting a biological response. They also observed a decrease in the response threshold for elongated cells oriented along the field. Note that the field induced by an alternating magnetic field 50 Hz 100 ÿT in a 1 cm sample on the solenoid axis by an order of magnitude less, ÿ 0.2 mV/m.

Blackman, Benan et al. [484] investigated the release of calcium ions from chicken brain tissue *in vitro* over a wide frequency range of combined exposure to weak magnetic and electric fields. The experimental formula was:

b(0.085–0.1)ep(20 V/m)f(1–510/15)Bp(< 38)B(?) .

We used dual control: sham control and control outside the exposure device. The rather small amplitude of the alternating magnetic field, tens of nT, is noteworthy, which corresponds to the level of some

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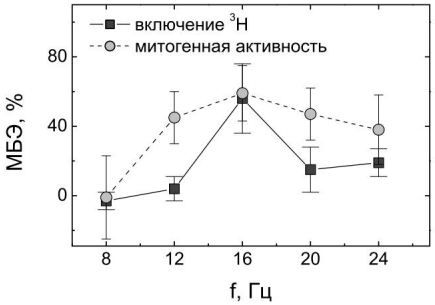


Fig. 2.41: Response of chicken skull bone cells to variable EP. Proliferation and mitogenic activity depending on bridges from the field frequency, according to data [440].

geomagnetic variations. For 16 of the 38 frequencies tested, a statistically significant, P < 0.05, MBE was found. Frequency windows were discovered MBE. The large frequency step, 15 Hz, is insufficient for drawing conclusions about the potential target of the magnetic field. It is possible that different primary biophysical mechanisms are triggered in different ranges. Important the observation was, however, that in almost the entire frequency range the MBE spectrum was of the same sign, the calcium release when the EMF was turned on increased.

Fitzsimmons, Farley et al. [440] investigated the proliferation of chicken bone tissue cells in a weak low-frequency electric field. the incorporation of 3H-thymidine into cells . The mitogenic activity of the exposed culture was also determined on another, unexposed one. A dish with a cell culture was placed between the plates of a flat capacitor, in the absence of galvanic connection. Alternating field between the plates, in the absence of a cup, was 10 B/2.3 cm. For- mule experiment

e(430 V/m)B(?)f(8–24/4)n(6)

allowed us to establish the presence of a frequency efficiency window, Fig. 2.41. Within the framework of the mechanism of ion interference in alternating electric field, section 4.6, the effective frequencies are the same as in in the case of a uniaxial magnetic field: the cyclotron frequency and its (sub)harmonics. If we take the local magnetic field, which was not reported in the article, as 20 ÿT, then the maximum frequency of 16 Hz corresponds to the Larmor frequency of ions calcium.

The activity of the ion-activated membrane enzyme Na,K-ATPase was studied by Blank and Coo in [323]. The suspension contained the substrate and the enzyme. To platinum electrodes, at a distance of 5 cm from each other, a sinusoidal voltage with an amplitude of

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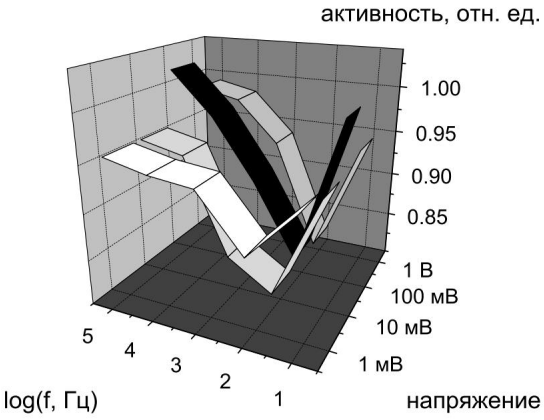


Fig. 2.42: Frequency windows of the relative activity of the enzyme Na,K-ATPase at different voltage amplitudes on the electrodes, according to data from [323].

from 1 to 1000 mV for 15 minutes. Accordingly, the electrical the offset for the smallest of the voltages was about 20 mV/m, The current amplitude in the circuit was about 70 ÿA/cm2. Frequency windows of efficiency were found with a maximum effect at 100 Hz, Fig. 2.42. These dependences can hardly be called spectral, due to the logarithmic scale of the frequency change. However, the frequency selectivity of the effect is obvious. The magnitude of the magnetic field was not controlled. The authors suggested that the processes of binding of Na and K ions by the enzyme involved in electroreception.

Amplitude dependencies were observed by Blank, Soo et al. in [339] with studying transcription processes in low-frequency electric fields. The HL-60 cell culture was studied by passing a current with a frequency of 60 Hz and a density amplitude of 0.1–100 ÿA/cm2. The maximum
A statistically significant 40% response was observed after 20 min of exposure to a current of 1 ÿA/cm2. At a current of 0.1 and 100 ÿA/cm2, the effect size amounted to 9 and 5%, respectively, at 10 ÿA/cm2 the effect was no different from the control. The authors note that their data do not support the hypothesis that the effect is proportional to the magnitude of the electric field. The data indicate the probable presence of an efficiency window in amplitude. internal electric field of about 10 mV/m, which approximately corresponds to a current density of 1 ÿA/cm2 in biological tissue.

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Liburdi [529] constructed a special dish with concentric cells, which was placed in a solenoid. The cells were arranged in such a way that it was possible to organize the passage of an alternating electric current of 60 Hz through a cell culture (rat thymocytes).
equal to that induced by switching on a 60 Hz, 22 mT MF
in the solenoid. In both cases, the electric field in the cell had one geometry and was 62–170 mV/m. Accordingly, the current density, with a measured specific conductivity of ÿ = 1.685 S/m, was
ÿ 10–30 ÿA/cm2.

The magnitude of the field correlated with the magnitude of the effect, concentration intracellular calcium, measured spectrophotometrically in real time. In these experiments, the alternating electric field, in any exposure variant, increased, after 10–
15 min, calcium concentration by 20–30% compared to the control.
Thus, the actual variable MP did not play a role here.
Using various biochemical methods, the author also identified the probable target of the field's action, the calcium membrane channel.

The article states that the solenoid axis of the GMP component is parallel was 20.5 ÿT, which, generally speaking, does not exclude ionic interference mechanisms of the electric field action.

Nazar, Paul and Dutta [585] found frequency selectivity
the effect of a sinusoidal electric field on the specific activity of the enzyme enolase in a culture of Escherichia coli cells. The cells were placed for 30 minutes in an area where the amplitude of the electric field
was 65.4 V/m. Frequencies in the range of 10–72 Hz were used. The effect, that is, the difference between the experimental and control activity values, referred to the control value, is shown in Fig. 2.43. It is evident that at
Varying the electric field frequency changed not only the magnitude but also the sign of the effect. The parameters of the local magnetic field were apparently not controlled. The motif of the figure is characteristic of the frequency spectra of the MBE
in low-frequency EMFs, although the authors determined the statistical significance of the effect only at a frequency of 60 Hz. There is a large average frequency step and a relatively large dispersion, so it is impossible
draw reliable conclusions. However, it is interesting to note the similarity between the data in Fig. 2.43 and the frequency spectrum of the MBE, also on E. coli, from work [245], see also Fig. 4.32. This similarity indicates the possible identical physical nature of the indicated biological effects of electric and magnetic fields.

Ko, Tutt et al. [633] studied the reorganization of cytoskeletal filaments by passing an electric current using a fluorescence video microscope.

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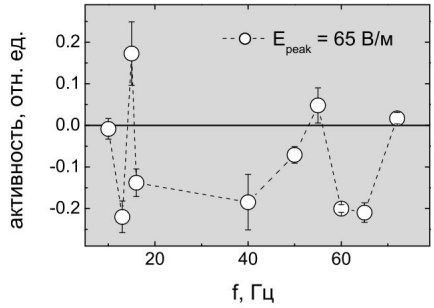


Fig. 2.43: Relative activity of the enzyme enolase in E. coli at different frequencies of the electric field, by data [585].

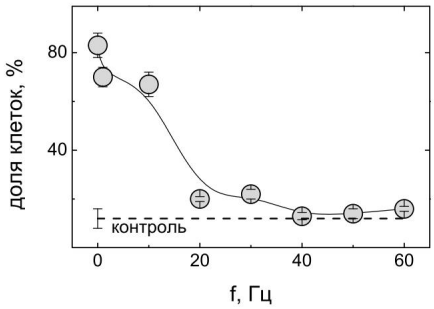


Fig. 2.44: Relative number human hepatoma cells responding to the inclusion of EP by restructuring the cytoskeleton 500 V/m depending on frequency. According to [633].

current through the culture of human hepatoma *Hep3B cells.* Parameters the electric field varied in the frequency range of 0–60 Hz, the zero frequency corresponds to the passage of direct current, and the field amplitudes were 0–1 kV/m. The latter were calculated based on the measured current and conductivity cellular environment. Only some of the cells responded to the field being turned on. Fig. 2.44 and Fig. 2.45 show the results, the relative number of sensitive cells that showed a reaction to 15 minutes of switching on.

fields. The non-resonant form of the frequency spectrum indicates that the effect is based on the reaction to a constant field with a characteristic time of 0.1 s, and fields of opposite direction cause

opposite effects. In this case, the action of positive and

negative half-wave of a sinusoidal signal with a frequency > 10 Hz

significantly compensate each other.

It is evident that the effect occurs already at a low electric field value of about 1 V/m and does not exhibit amplitude selectivity. The basis of such effects, characterized by the absence of

frequency-amplitude windows, the mechanisms of activation may lie

type described in section 3.4.

The rate of glycolysis of mouse brain astrocytes in the presence of electrical

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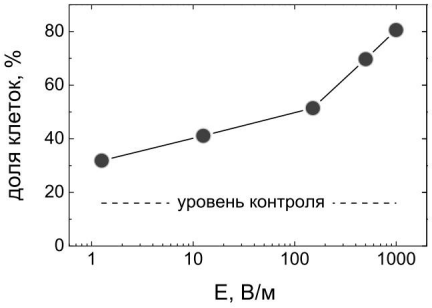


Fig. 2.45: Relative number
lo of human hepatoma cells that respond by restructuring cytoskeleton tours for inclusion EP 1 Hz of different amplitude. According to [633].

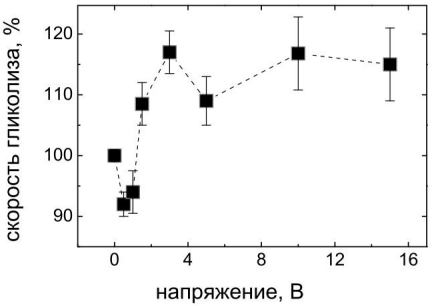


Fig. 2.46: Rate of glycolysis
mouse brain cells after 30 minutes exposure to an electric field a given value, as a percentage of control at U = 0V, according to data [475].

field strength of 50–1500 V/m was measured by Huang, Peng, and Hertz [475]. The cell culture in a flat dish was located between horizontal capacitor plates separated by a distance of 1 cm. When the negative electrode was on top, an increased speed was observed glycolysis, by approximately 20% at 1000 V/m. Changing the polarity changed the sign of the effect, but it was much smaller in magnitude, about 4%. It is interesting that the dependence of the magnitude of the effect on the tension The field had a non-trivial character, Fig. 2.46.

Considering that the cell culture with a dielectric constant of > 50 and the bottom of the dish with a permeability of ÿ 5 occupied 1 mm (size cells of about 0.01 mm), the authors calculated that the cells were in a field of ÿ 30 mV/m when a voltage of 15 V was applied. Even such a relatively small electric field is capable of causing biological an effect with a complex dose dependence. The authors suggest that a static electric field can influence the orientation of the electrically charged protein Na+,K+-ATPase in the cell membrane and, consequently, the concentration of extracellular K+. The asymmetry of the response to a change in field polarity could be caused by the preferential orientation of cells either in the gravitational or in the unaccounted for

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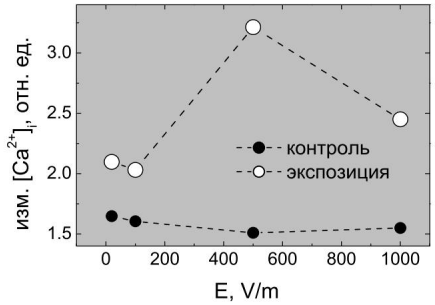


Fig. 2.47: Intracellular calcium concentration in a mouse osteoblast culture after exposure to 10 Hz EF of varying amplitude. According to data from [689].

local magnetic field.

Sontag in [668] applied a low frequency electric field to medium with HL-60 cells by means of flat electrodes inside or externally in the amplitude range of 1–4000 V/m and frequencies of 0.1–100 Hz. Measurement of the intracellular content of free calcium ions on a fluorescence spectrometer did not reveal the effectiveness of a 15-minute exposure to such fields. The GMF component perpendicular to the electric field was 12 ÿT, the presence and magnitude of another component nothing reported. The effectiveness of current exposure is 250 ÿA/cm2 at a frequency of 4 kHz in an amplitude window of about 200 ÿA/cm2 was discovered in one of the following works [669] on measuring the output interleukins from cells. Low-frequency modulation was used here. current with a frequency of 0–125 Hz.

Tang, Chen, and Zhao [689] studied the proliferation of mouse osteoblast cells. Cells exposed to 10 Hz, 20 V/m EF in within 20 minutes, they grew 60% faster than the control group. They also measured intracellular calcium concentration by the fluorescence method exposure to rectangular pulses of the EP according to the following scheme

e(20–1000 V/m)f(1–1000) .

Frequency and amplitude windows detected. Maximum effect found in the range of 5–15 Hz. The amplitude spectrum is shown in Fig. 2.47 and demonstrates the maximum effect of EP in the region of 500 V/m.

2.6.2 Frequency-amplitude windows

Among the above experiments, two groups can be distinguished: depending on the method of applying the electric field. In the first

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Table 2.2: Experiments with externally applied EP

Wednesday	f, Hz	E, V/m	Effect
Brain tissue enriched with 45Ca	3–24	10-60	-15% Ca leakage [266]
Bone cell culture	12–20	430	+50% proliferation cells [440]
E. coli cell culture 10–70		65	-20% special activity enolases [585]
Osteoblast cells mice	5–15	500	>50% proliferation and the concentration of [Ca2+]i [689]

In this case, the system under study is placed between the plates of the condenser.
ra, without direct electrical contact. In the second case, current is passed through electrodes inserted into the biological environment. In
In both cases, windows of efficiency of electrical parameters are observed.
Czech field.

The data for the first group are summarized in Table 2.2. All experiments contain only a few experimental points, which are difficult to associate with any smooth curve. However,

we can draw a general conclusion that effective electric fields are characterized in the order of magnitude by intervals of 10–100 Hz in frequency and
10–100 V/m in amplitude.

In the second group of experiments the measured quantity was current, passed through a physiological medium containing the cells being studied. In this case, the internal electric field can be
calculated knowing the conductivity of the medium. The experimental results are summarized in Table 2.3. From the table it follows that the expected ranges of efficiency in such experiments are 10–100 Hz and 1–
10 ÿA/cm2, in order of magnitude.

The expected efficiency frequency windows of 10–100 Hz coincide for both groups of experiments. The Larmor and cyclotron frequencies are the main ones from the point of view of any mechanism utilizing
the idea of ions' involvement in the biological reception of electromagnetic fields. These frequencies fall precisely within the specified range for the majority of biologically important ions in magnetic fields of the order of the geomagnetic field.

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Table 2.3: Current Passing Experiments

Wednesday	f, Hz	J, ÿA/cm2	Effect
Fibroblasts in a collagen medium	1–10	> 1	-30% DNA synthesis [565]
Suspension substrate-enzyme	20–1000	> 70	-15% activity Na,K-ATPase [323]
HL-60 cell culture 60		0.3–3	+30% transcription level [339]
Rat thymocytes	60	20	+25% concentration [Ca2+]i [529]
Fibroblasts in a collagen medium	10–100	5–7	+60% DNA synthesis [450]
HL-60 cell culture 0-100	(mod)	200–400	+100% interleukins output [669]

Regarding the amplitude windows, we note the following. In the first group of experiments, the average electric field inside the medium decreases approximately two orders of magnitude compared to the external field due to dielectric polarizability of water with ÿ ÿ 80. The effective dielectric constant of the medium can increase several times more due to the special properties of the double electric layer surrounding the charged surface of the cell membrane [342]. This means that that the effective internal electric fields in the medium are equal in order of magnitude to at least 100–1000 mV/m, or probably even higher several times less.

In the second group of experiments, the internal EP can be determined from the relation E = j/ÿ, where j is the current density in the medium, ÿ — conductivity of the medium. For biological tissues ÿ ÿ 1 S/m. Therefore, the range of effective fields corresponds to the interval 5–500 mV/m. Thus, there is also an approximate match and amplitude windows in both groups of experiments. The question arises about the possible physical equivalence of the specified windows in the effects EP applied to the environment in various ways. In any case, there is no reason to claim that the underlying physical mechanisms are different the basis of biological effects in the two groups mentioned. Further, in Sections 4.6 and 4.9.6 show that quantum interference of ions can explain the biological effectiveness of weak EPs, regardless of

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simo from the method of its delivery to the micro level.

Some other experiments on DNA-RNA synthesis, activity enzymes, cell proliferation and calcium transport, showing window spectra of the effectiveness of electromagnetic exposure are given in a brief review by Berg [282]. They also indicate the existence of an optimal frequency-amplitude regime in the frequency region 10–100 Hz and field amplitudes of 10–100 mV/m.

2.7 Biological effects of ultraweak fields

Experiments showing the biological activity of ultra-weak magnetic fields are gradually accumulating. There is no data yet on the dependence of these effects from the level of constant magnetic field at the place where the experiment was conducted. Because the average intensity of the alternating magnetic field in these observations is significantly lower than the possible level of a constant field, it is appropriate to separate such experiments into a separate group. The mechanisms of the biological effectiveness of ultra-weak fields are likely different from those of geomagnetic fields.

Early experimental evidence of biological detection of ultra-weak variable signals, such as magnetic ones, up to 1 nT, both electrical and electrical, up to 0.1 mV/m are given by Presman in [164]. Sensitivity the sensitivity of sea sharks and rays to fields of intensity up to 0.5 μV/m is discussed by Bastian [263].

Changes in peroxidase activity in peripheral leukocytes blood of rabbits after 3 hours of exposure to ultra-weak MF of 8 Hz frequency was observed by Vladimirsky, Volynsky, and others [222] already in 1971. The range of magnetic field strengths in the experiments included 0.02, 0.2, 1 and 2 nT. Changes in cytochemical activity were observed at all values. neutrophils compared to controls. Changes ranged from approximately 9±2% at 0.02 nT to 72±23% at 2 nT. The authors believed that this could be evidence in favor of a direct effect geomagnetic storms on living systems.

Keeton, Larkin and Windsor [507] reported that natural GMF fluctuations (ÿ 100 nT) affect the orientation of pigeons.

In [420], Delgado, Leal et al. investigated changes in the morphological parameters of growth of chicken embryos under the influence of pulsed magnetic fields for 48 hours. The volume of data is insufficient to construct amplitude or frequency spectra, but statistically

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significant efficiency of 0.12 ÿT 100 Hz and 1000 Hz modes is shown.

Ree, Pan et al. report in [415] that the 16 people they studied had sufficient sensitivity to EMF to distinguish the switching on of the magnetic field. In the area where the subject was located, the switched on
MP was non-uniform and varied from 2.9 ÿT in the feet area,
0.35 µT near the knees and 70 nT near the head.

The influence of a sinusoidal field with frequencies of 0.05–5 Hz with intensity about 100 nT on the impulse activity of neurons in the cerebellar slice
Mice were observed by Agadzhanyan and Vlasova [1]. The experiments were conducted in a chamber protected from external magnetic interference.

Jacobson [490] used it to treat epilepsy and disease
Parkinson's variable MP level picotesla, from 5 · 10ÿ12 to 2.5 ·
10ÿ11 T. A sinusoidal field of 2–7 Hz was applied to the head
brain so as to affect the pineal gland. Stimulation by such MP
correlated with melatonin production.

Kato, Honma et al. [626] determined the effect of circularly polarized 50 Hz 1 ÿT MF on the nocturnal melatonin concentration level in
blood of rats. Animals placed in a similar environment served as controls.
exposure chamber with a residual field < 0.02 ÿT. The melatonin concentration at the end of 6 weeks of exposure in both chambers was 81.3 ± 4.0 pg/ml for the control group and 81.3 ± 4.0 pg/ml for the exposed group.
group 64.7 ± 4.2 pg/ml. This difference disappeared if measurements were taken one week after cessation of exposure. Probably, the division
into the control and experimental groups is rather arbitrary here, since exposure to fields of such low intensity is in itself not indifferent to animals. However, in any case, the effectiveness of fields of this level
1 µT is shown.

A series of works by Novikov et al., see, for example, [143, 196], is devoted to the study of the polycondensation reaction of molecules of certain amino acids
in solutions exposed to an alternating magnetic field of about 20 nT parallel to a local constant magnetic field of the order of the geomagnetic field. The MF frequencies were several Hz, which corresponds to
cyclotron frequencies of amino acid molecules. Unfortunately, the authors did not reported how they determined the cyclotron frequencies of amino acid molecules. This is important because the electric charge of these molecules in
The effectiveness of the MP in a solution depends on its acidity. At the same time, the very fact that it is effective at such a low level has been demonstrated quite convincingly. On reproducing similar experiments in independent laboratories
It is not known.

Blank and Soo in [324] determined the limit of sensitivity of the active

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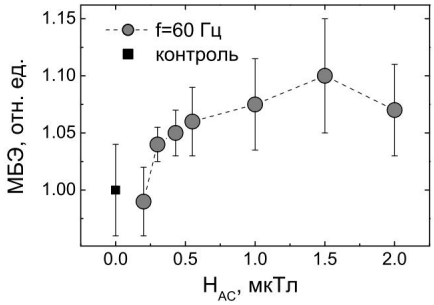


Fig. 2.48: Activity of membrane ion pump under action ultra-weak variable magnetic field, according to [324].

the activity of the enzyme Na,K,-ATPase in the medium with microsomes in relation to Industrial frequency MP. The sensitivity limit was 200–300 nT, Fig. 2.48.

West, Hinson, and Swickord [717] found that 60 Hz MP of magnitude 1 ÿT, against the background of a static laboratory MF, exposed to Over the course of several days, application of JB6 mouse epidermal cell culture resulted in a 1.2–2.4-fold increase in cell numbers compared to the control.

In [225], Akerstedt, Arnitz et al. investigated the effect of night exposure to 50 Hz, 1 ÿT MF on various physiological characteristics of human sleep (18 people took part in the experiments). It was It was found that such an MP significantly shortened the so-called slow phase sleep.

Harland and Liburdi found in [469] that the 60 Hz MF is 1.7 µT (and even 0.28 ÿT)

b(1.7)bstray(< 0.06)B(< 0.3)Bp(< 0.3)f(60)

suppresses the inhibitory effect of melatonin and tamoxifen. Melatonin at a physiological concentration of 10ÿ9 M and tamoxifen at a pharmacological concentration of 10ÿ7 M were used to inhibit growth human cancer cells MCF-7. In view of the importance of these data, indicating the potential danger of even such weak fields, the work was reproduced in another laboratory by other researchers, see Blackman, Benan and House [318]. In both cases, the results were similar, the inhibitory effect was reduced statistically significantly by tens of percent.

A series of experimental works was carried out by various scientific groups with the device Tecno AO, Tecnosphere, France, patent 93/00546 [413]. The placement of the device near the object being studied (chicken embryos, experimental groups of people) is as if

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compensates for harmful radiation from video monitors and cell phones [730]. The device is a metal vessel of a certain shape, filled with a special aqueous solution. The nature of the active agent is still unknown. However, it is most acceptable, with
orthodox point of view, to associate it with an ultra-weak magnetic field, modified by the action of radiation on the solution. The level of such radiation,
ÿ 1 fT, can be estimated from the relation (see section 1.4.2)

$$cH2/4ÿ = S = ÿ \quad \frac{1}{4ÿr2} \frac{\overline{NA}}{ÿr} ,$$

where the right-hand side is the energy flux density at a distance r from the volume of the solution of the order of 1 M, ÿ is the 1H NMR frequency in the geomagnetic field, ÿr is the spin-lattice relaxation time; the radiation power is proportional to the square root of the number of independent emitters.

Biological effects of ultra-low intensity *microwaves* have been observed in several studies: 10ÿ2 ÿW/cm2 [587], 5 10ÿ6 ÿW/cm2
[463], 10ÿ12 ÿW/cm2 [635]. The yeast culture *Saccharomices c.* was exposed to 7.1 mm microwaves in a wide power range
Kuznetsov, Golant and Bozhanova in the work [120]. The response consisted in the emergence in a synchronous cell culture of a special type of proliferation process, when the dependence of cell concentration on time
had the form of a step function. This type of response arose after some time t after the start of irradiation, and this time depended on the microwave power. A dependence close to linear (from the logarithm of the power) was measured within t = 5 min at 1 mW/cm2 and
t = 240 min at 10ÿ12 ÿW/cm2. It is interesting to note that the value 10ÿ10–10ÿ11 ÿW/cm2 corresponds to the sensitivity threshold of the receptor tori of sight and hearing.

At present, the physical nature of biological effects
weak variables of the magnetic field, of the order of the geomagnetic field, remains unclear. Therefore, experimental data on the biological reception of magnetic fields are still 3-10 orders of magnitude weaker look, of course, defiant. Volume
There is still little data on this subject, but it is accumulating.

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Chapter 3

Theoretical models MBE

The answer to the question of how a weak, about 1 Gs or less, low-frequency magnetic field causes a biological response cannot be
be given in simple form. The formation of the magnetobiological effect is significantly influenced by processes at different levels of organization of a living organism, from the physical to complex
adaptive biological processes [205]. Specialists in different fields of science answer this question in their own way. Doctors distinguish
In the body, organs and general physiological processes are sensitive to magnetic fields. Biologists are trying to find the cellular and subcellular structures that generate biological signals in response to the field.
Biochemists are looking for targets - links in biochemical reactions, speed
which could depend on the parameters of the magnetic field. Within the framework of (bio)physics are trying to identify magnetically sensitive interaction processes
MP with relatively simple molecular structures. It is on
At this level, complex spectral or "window" modes arise
connections between biophysical processes and biotropic parameters of magnetic field.

This chapter critically examines hypotheses and models (including some original work by the author) of biological reception
weak MP. Review of possible mechanisms of magnetoreception of strong
MP, from fractions of Tesla and more, made by Piruzyan and Kuznetsov in the work [161].

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3.1 State of theoretical research in magnetobiology

It is advisable to begin the analysis of the state of the theory of magnetoreception by identifying groups of similar explanations of magnetobiological effects.
Such groups exist, which leads to the emergence of conditional classifications of magnetobiological models. Polk [610], Adie [239], Berg and
Zhang [283] classifies the mechanisms of MBE. The presence of classifications,
Their inherent ambiguity and rapid aging reflect the difficulties in explaining magnetobiological effects, their paradoxical nature, and the incompleteness of knowledge about the nature of the biological effectiveness of weak electromagnetic fields.

Today, in development of the above-mentioned review works, it would be possible to identify groups of physical processes or ideas [298] that presumably underlie magnetoreception, dividing them by the type of description: phenomenological, macroscopic and microscopic.
A phenomenological description does not touch upon the nature of a phenomenon, offering only mathematical means for describing the external manifestations of an object. Conversely, macroscopic and microscopic descriptions reveal the physical essence of an object and establish its boundaries.
applicability of specific phenomenological models. They differ from each other in the scale of the objects of description.

There is also a special group of theoretical works, the essence of which
We will illustrate this with the following general considerations. The thesis that A as a physical phenomenon *exists* is comparatively easy
prove. It is enough to experimentally confirm its presence when
some specific conditions, no matter what, from a range of admissible ones. At the same time, the opposite thesis, that A as a physical phenomenon *does not exist,* is much more difficult to prove. To do this, it is necessary to confirm the validity of this thesis under *all* admissible conditions.
conditions. Often, it is not possible to go through all the possible conditions, even mentally. seems possible. This is precisely the case with the phenomenon of biological reception of weak MPs. Its confirmation is a matter of scientific practical activity.
Within the framework of the concepts of positivism, the thesis
that the IBE does not exist, is falsified by the entire set
experimental data. It is impossible to disprove the existence of this phenomenon either experimentally or by formal logic. In the latter case, the enumeration of conditions, that is, possible mechanisms of MF action, cannot be completed. There always remains the possibility that some special conditions have not yet been considered.

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Nevertheless, despite the logical inconsistency of attempts to theoretically refute the MBE, such attempts are being made. For relevant works, see, for example, the articles by Adair [235, 236], as well as
Bioelectromagnetics, 19:136, 1998; 19:181, 1998; 22:97, 2001, contain
physical models of the hypothetical processes underlying the MBE proposed in the literature. However, since the models are aimed
to refute, they do not contain a constructive element and have no predictive power. The substantive statements of these works
It is impossible to verify. Therefore, such models are not considered in the book.

3.1.1 Classification of models of MBE mechanisms

The following classification is to some extent arbitrary, and the choice of specific works representing the group is subjective. It is not always possible
unambiguously classify the work into one group or another. The author does not claim to be comprehensive, and does not claim that the models considered are better
or worse than other models in the same group. At the same time, such a division turns out to be convenient, allowing us to analyze not specific ideas, mechanisms, models, and their *types.* The classification does not include mechanisms biological action of strong MPs. A review of such ideas, including
diamagnetic orientation, liquid crystal effects, redistribution of molecules in a non-uniform magnetic field, magnetohydrodynamic
effects are given, for example, in the work of Kuznetsov and Vanaga [119], and the corresponding experiments are given in the monograph by Simon [662]. Here we we focus only on *a priori* probable root causes of MBE,
- bioeffects of weak magnetic fields.

Phenomenological models

- complex behavior of solutions of equations of the chemical type
kinetics [568, 497, 444]
— stochastic resonance as an amplifying mechanism in magnetobiology and other random processes [131, 513, 287]
— magnetosensitive phase transitions in biophysical systems considered as liquid crystals [176] or ordered
membrane proteins [227]
—“radio engineering” models in which biological microstructures and tissues are depicted as equivalent electrical circuits
[494, 604, 254, 260]

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Macroscopic models

— biomagnetite in a magnetic field and ferromagnetic pollution [28, 511]
— Joule heat and eddy electric currents induced by alternating magnetic fields [344, 409, 608]
— superconductivity at the level of cellular structures [354, 355, 620, 233, 356] and alpha-helical protein molecules [366]
— magnetohydrodynamics, see review [119]
- macroscopic clusters of ions, charged vortices in the cytoplasm [102]

Microscopic models

— the motion of charged particles and particles with spin in magnetic fields, including resonance effects [409, 332, 519, 26]; oscillatory effects [621, 277, 125, 88]; interference [293, 297, 296, 300]; reactions involving free radicals [35, 678, 329]; collective excitations of multiparticle systems [442, 72, 725]
— biologically active metastable states of liquid water, sensitive to MP variations [107, 290, 617, 3, 23]

The depth of development of these ideas varies greatly. Only a few of them have been implemented in the form of mathematical models with predictive power. Apparently, a theoretical explanation of a phenomenon is valuable when it allows for comparison with experimental data. What is important here is the ability to compare not numbers, but functional dependencies. That is, the theory must be able to calculate the magnitude of the effect depending on the parameters of the magnetic field. Therefore, mechanisms that do not meet this rule, and they are the majority, are not analyzed in detail, but only mentioned. Criticism of such mechanisms is excluded due to the fundamental impossibility of using a comparison of theoretical predictions and experimental data—the main criterion

the truth of scientific judgments.

Macromodels of MBE form a more or less independent group. Phenomenological models, on the contrary, require microscopic justification. Thus, models based on specific solutions of chemical kinetic equations require refinement, the rate which of the chemical reactions and how does it depend on MP? When considering stochastic resonance, it is necessary to indicate which resonance physical object in mind. Models with magnetic sensitivity-

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Phase transitions require specification of the objects interacting with the magnetic field. In general, such objects are microparticles possessing charge and/or spin. One way or another, all non-macroscopic mechanisms rely on the special dynamics of particles.
in MP. Dynamics, classical and quantum, provides the basis for theoretical consideration of the IBE, especially the paradoxical IBE character.

Works devoted to the dynamics of particles in the MF to explain the MBE, quite a lot. Almost all of the proposed mechanisms are implemented as models. Therefore, it is advisable to classify them within
this group of models by the type of dynamics, classical or quantum, and by the type of variable changed during the interaction of particles with MP. This classification is completely objective, and therefore convenient for comparing model types.

Before giving this classification, we note some non-trivial
differences and similarities in the behavior of single-particle and multi-particle systems
stem. Almost all objects that have to be dealt with in
In physics, they are multiparticle systems. However, it is often possible to isolate more or less isolated particles whose motion
is determined only by the combined action of all other particles. The latter, as it were, create an effective potential for the movement of the selected particles. In this case, single-particle models are able to display the main properties of the selected system. Such, for example, is the model of an atom, in which each of the electrons is satisfactorily described the combined potential of the nucleus and the cloud of other electrons. Rotations molecules in the gas phase is another example. Single-particle models satisfactorily describe many physical systems. They
extremely convenient and visual, although not always accurate.

The motion of several particles is usually analytically unsolvable. It is extremely complicated. In some
In cases where the bonds between particles lead to the emergence of structures that are more or less symmetrical in equilibrium, it is possible to determine the generalized coordinates of a multiparticle system, the number of which is proportional to the number of particles. The motion of the system can then be represented in in the form of a superposition of independent motions along these coordinates. Vibrational spectra of symmetric molecules, for example, can be studied analytically using group theory if the number of atoms
in order does not exceed ten.

With a further increase in the number of particles and with a sufficiently strong interactions lead to *collective* coordinated movements

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particles, the so-called collective excitations or dynamic modes of oscillations. Usually, this situation is described in the so-called continuum (or continuous medium) approximation, when instead of the coordinates of particles, their continuously changing density is introduced. Mathematically, the dynamics of such modes is equivalent to the oscillations of single-particle systems and is therefore also convenient and intuitive. The dynamic variable in the classical In this case, the amplitude of collective excitation is used, in the quantum case, number of excitation quanta. Interaction with the magnetic field can lead to pumping of excitation energy, which could serve as a mechanism for MBE. The original works looked at collective excitations, vibrations of biological membranes, waves of shear and torsional displacements in biopolymer molecules [577]. However, the natural frequencies of such collective excitations fall in the microwave range. Collective excitations of biophysical structures in the range of interest to us of the order of 1–100 Hz are unknown. In view of this circumstance, we will limit ourselves to a summary of single-particle models of MBE mechanisms for which natural frequencies of the order of

ÿ qH/M c. For particles such as biologically significant ions with mass M and with a charge q in a field H of the order of the geomagnetic field, these frequencies fall into the specified range. A summary of the models, by groups of dynamics and the variable on which the MP acts, is given in Table 3.1.

3.1.2 Brief description of the MBE mechanisms

Let us give a brief description of the frequently discussed mechanisms of magnetoreception, which are believed to be the basis of MBE.

One of the earliest ideas in magnetobiology involves so-called biogenic magnetite in a magnetic field. Microscopic crystals, usually magnetite, that can be magnetized naturally form in the bodies of some animals and microorganisms.

In an external magnetic field, such crystals experience a rotational moment and exert pressure on nearby tissues, which causes a biological reaction. Apparently, this mechanism, consistently studied by Kirschvink [553], actually takes place. Crystals magnetite has been found in the brains of some birds known to have a pronounced ability to orient themselves in the geomagnetic field field, in some insects and bacteria.

Explanation of the biological effect of low-frequency magnetic fields on cells *in vitro* taking into account ferromagnetic contamination [511] develops the idea biogenic magnetite. Contaminating magnetic particles are present not only in the dust in the air, but also get into chemicals and water.

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Table 3.1: Classes of processes for transforming changes in the MF into changes in the particle motion variables and the corresponding MBE models

Object of influence of MP	Charge dynamics	
	Classical	**Quantum**
Coordinate	Motion under the action of the Lorentz force: deviation parts- tsy [9]; polarization fluctuations [384]	Interference of states: [22, 293, 297, 296, 304, 300, 303, 305]
Pulse, moment of impulse sa, energy	Energy pumping: cyclotron resonance [524, 734]; parametric [409, 88] resonance	Quantum transitions: in the Emanov and Stark sublevels [621]; parametric resonance [519, 320]
Spin	-	Spin dynamics: spin resonance [27]; reactions with participation of the RP [36]; exchange reactions [290, 26, 23]; interference of states taking into account spins [293]

According to the authors, such particles, being adsorbed on the cell surface, can transfer their energy, for example, to mechanically activated ion channels.

These magnetoreception mechanisms stand apart and do not solve the main problem of magnetobiology. After all, unicellular organisms, in which magnetite is absent, are also capable of responding to a magnetic field. Moreover, the reaction in many cases is complex, nonlinear, and polyextreme, depending on the field parameters. The main problem of magnetobiology lies precisely in explaining this phenomenon, paradoxical from the point of view of traditional physics.

Sometimes the biological effectiveness of weak MPs is explained by based on the representation of biological tissue or biophysical structures as equivalent distributed electrical circuits. In any case, this approach, being phenomenological, does not solve the problem of magnetobiology. Even the descriptive possibilities of such approaches are questionable. Thus, in *Biophysics, 38(2):372, 1993* they explained the influence of constant magnetic field on the process of propagation of the potential of action

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action along the nerve fiber. At the same time, the ion channels of biological membranes were presented in the form of oscillatory circuits with electric solenoids. These microsolenoids produce magnetic fields when their channels are open and thus interact with each other and with external MP. The basis for this idea was, on the one hand, sides, the fact of experimental measurement of the intrinsic inductance and capacitance of sections of biomembranes and, on the other hand, the assumption that the ion in the ion channel moves in a spiral. However, in [25] it is shown that 1) the equivalent inductance reflects only the inertia of ion channels when the voltage changes, 2) the movement of the ion inside the channel is unlikely to be of a classical nature, 3) the movement of ions in the channel occurs alternately, MP of such movement, even if it is a classic movement along a spiral trajectory, far does not correspond to the magnetic field created by charges moving simultaneously in all parts of the solenoid. It is clear that any explanation based on the model of ion channels-solenoids is no more than an illusion of explanation.

The hypothesis that the active factor in the irradiation of biological systems with low-frequency magnetic fields is eddy electric currents induced by alternating magnetic fields has been repeatedly tested. biological tissues. They can lead to tissue heating (see Section 1.4.1). Polk showed that eddy currents can also cause electrochemical effects due to charge redistribution [608]. The currents are determined by the strength of the induced electric field, which is proportional to the product of the amplitude and frequency of the magnetic field.

If the hypothesis is correct, then the MBE in the experiment should have correlated with changes in this value. Indeed, there is experimental evidence that such a correlation appears with an increase in the intensity of the alternating magnetic field [521, 652]. However, there are no correlations in in the case of relatively weak magnetic fields, of the order of geomagnetic, it was discovered was not [496, 527, 642, 316, 491, 615]. Thus, in [642] the MBE in a certain frequency window remained unchanged when varying the value induced currents by almost 40 times. This indicates the existence primary mechanisms of MBE not associated with eddy currents.

The informational or signaling nature of the action of weak physicochemical factors on biological systems is often discussed. This implies that the biosystem is in a state close to a state of unstable dynamic equilibrium. Therefore, it is only necessary to nudge the system and it will transition to another state. at the expense of internal resources. In other words, the so-called bio-

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logical amplification of a weak MP signal. For phenomenological
Descriptions of this process use the equations of chemical kinetics.
Under certain conditions, their solutions exhibit bifurcation behavior, a transition
under the influence of a weak perturbation to a qualitatively different dynamic
regime. In application to electromagnetobiology
This approach was discussed by Kaiser [497].

An important question is: why do thermal fluctuations, the energy scale of which is ten orders of magnitude greater than the quantum of magnetic field energy,
don't destroy the MBE? The solution is associated with the idea of the coherent
effect of an external factor against the background of incoherent thermal noise. Then
it is possible to swing any high-quality oscillator (temporal coherence) to a state
in which its energy will be sufficient for the initiating impulse, or to swing the
system synchronously
oscillators (spatial coherence), so that a quantum of collective excitation energy
is released [441, 414]. Another version
is that it is not energy, but some other parameters of the oscillator, such as the polarization of oscillations, that are acquired under the influence of magnetic fields
properties that are important for the operation of the associated biophysical
systems. For example, Zhadin and Fesenko [734] and Edmonds [384] discussed
the application of Larmor's theorem to an ion bound in a microcavity
calmodulin. The central idea was that the direction of the ion's oscillations has a
decisive influence on the protein's shape, which in turn causes a change in
enzymatic activity. Within the framework of classical dynamics, the change in the
direction of oscillations in
alternating magnetic fields of various configurations. The Larmor frequency is
noted to be particularly important in terms of the expected effects of perpendicular
magnetic fields. It is also unclear why a parallel configuration of alternating and
direct magnetic fields can alter enzymatic activity. However, this is precisely the
configuration that proves most effective in many experiments.

Various microscopic level objects, molecular groups, plasma membranes and

entire organelles. It is significant that neither the idea of an oscillator nor the idea
of collective excitations has yet led to the construction of predictive mechanisms.
Wu [725] showed that there are threshold times
exposure of a biological system and the threshold amplitude of microwave
radiation required for the occurrence of a biological response
clique.

Another idea for overcoming the thermal factor appeals to the so-called
phenomenon of stochastic resonance. The phenomenon consists of amplifying a small

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signal against a background of noise due to the redistribution of energy in the spectrum of the additive mixture of signal and noise. The fundamental point is that the presence of noise This is not a hindrance, but a useful property of the system. Under conditions of stochastic resonance, relatively weak biological signals can lead to significant changes in the behavior of a dynamic system.
systems against the background of the action of various, relatively strong, disturbing factors. In [721] it is reported that the reaction of mechanoreceptor cells of crayfish to an acoustic stimulus in the form of a subthreshold
signal mixed with Gaussian noise satisfied the criteria of stochastic resonance. To solve the "kT problem" the phenomenon was used in [131, 513]. However, the actually obtained gains were of the order of a hundred, with
loss of signal quality, its coherence [566], are far from sufficient
to explain the biological effectiveness of weak low-frequency
MP.

The rate of some reactions involving free radicals depends on the magnitude of the constant magnetic field [35]. The probability of formation of a product from two radicals carrying spin angular momentum depends on
their total moment, i.e., from the mutual orientation of the spins. A constant magnetic field influences the probability of a favorable orientation occurring and, thus, is capable of shifting the biochemical balance. Together with
However, this mechanism does not have frequency selectivity. The lifetime of a radical pair before reaction or, conversely, before dissociation,
that is, in a state in which the radical pair is sensitive to MP,
is of the order of 10ÿ9 s. Low-frequency MF is perceived by the couple as constant field, resonances do not occur. Therefore, to explain
extreme dependences of the MBE on the parameters of the magnetic field Grundler, Kaiser and others believe that the magnetosensitive free radical
the reaction is a link in a system described by a system of nonlinear
equations of chemical kinetics [568, 497] with bifurcations. The difficulties of this group of models are still associated with the primary process of the action of an alternating magnetic field on the rate of a radical reaction. There are a number of physicochemical factors limiting the sensitivity of velocity to magnetic fields to values of the order of 1%/mT, which is insufficient for a reliable explanation of the bioeffects of weak variable magnetic fields with an amplitude
about 50 ÿT and less.

In some cases, the effects of weak magnetic fields have a resonant character, and the effective frequencies are close to the cyclotron frequencies of the ions Ca2+, Na+, etc. Libau suggested that cyclotron resonance lies
at the basis of the observed phenomena [524]. The theme of such resonance in magnetobiology was developed by various authors, but did not receive recognition because

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due to the difficulties of correct physical justification. At the same time, these experiments demonstrated the significant role of ions, especially Ca^{2+} in magnetobiology. It is important to note that the coincidence of effective frequencies with cyclotron frequencies is not a convincing argument in favor of the idea of cyclotron resonance in biology. For example, *any* theoretical model of MBE based on the dynamics of electric charges will operate with characteristic frequencies

$\omega_c = qH/Mc$. There is no other combination of charge and magnetic field parameters with the dimension of frequency.

To overcome the shortcomings of the cyclotron resonance idea, Macroscopic charged structures in biological plasma, vortices formed by ion clumps, have been postulated [101]. Such targets for the action of weak magnetic fields are chosen based on considerations of their sufficiently large self-energy, comparable to ωT . Then, even A weak magnetic field can significantly alter the energy of an object carrying, for example, a macroscopically large electric charge. However, this requires a certain condition: the movement of the center of mass. the object must have angular momentum [26]. The possibility of such a macroscopic motion is questionable. Moreover, for the comparison of vortex energy with ωT to be meaningful, a mechanism is needed transformation of the energy of a macroscopic vortex into the energy of a separate degrees of freedom, that is, to the microscopic level. It is difficult to imagine such a mechanism. The nature of the molecular forces is also unclear, capable of ensuring the existence or stability of such an ion cluster.

Some magnetobiological effects of a magnitude-modulated magnetic field exhibit efficiency bands in frequency and amplitude of the magnetic field. The spectra of the dependences of the magnetobiological effects on the magnetic field parameters are very informative in terms of identifying the primary mechanisms of magnetoreception. To explain the spectra, we used mechanisms for converting the magnetic field signal at the level of microscopic dynamics, classical and quantum models of the binding process of certain ions

proteins [343, 621, 519, 88]. The biological activity of a protein depends on the presence of the corresponding ion in a bound state. It was assumed that the magnitude of some magnetobiological effects is associated with the intensity of transitions in the quantum levels of the ion, which changes under the influence of a magnetic field. But parallel static and low-frequency magnetic fields, affecting only the phases of wave functions, in fact, do not cause transitions in Zeeman sublevels and do not change the intensities of transitions caused by other

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factors. The population of each state remains constant.
regardless of the MP parameters. Despite this, in [519] it was possible to show the similarity of the amplitude spectra of some MBEs with similar amplitude dependencies in the parametric resonance effect in atomic spectroscopy [7], where the characteristics of quantum transitions are studied. This has led to a number of publications [320, 125, 88], which, however, This similarity was not further clarified. The above discussions
The authors call these mechanisms parametric resonance of ions.

The phenomenon of interference of quantum states, known in physics used by the author to explain the physical nature of magnetoreception in works [293, 294]. Varying in magnitude, but not in direction, the magnetic field changes only the phases of the wave functions of the charged particle.
It is the interference that connects the changes in the phases of wave functions with observable quantities. Interference of quantum states is observed in physical measurements either for free particles, including
number of relatively heavy particles, up to atoms, or for bound particles. In the latter case, the interference of particle states is observed
only by the characteristics of the re-radiated electromagnetic field.
This reduces the particles whose interference can be observed to electrons in an atom. The assumption that the interference of states of heavy bound particles, ions, can also be observed and used
for this purpose, indirect non-physical measurements involving natural active biophysical structures, is original and finds
confirmation in good agreement with experiment [293, 297, 296]. The interference of bound ions can be considered as a previously unknown physical effect, which is registered in principle only
biochemical or biological means. A well-known phenomenon
interference of quantum states in atomic spectroscopy is associated
with coherent quantum transitions in the atom and is not associated with the internal structure of the electron's wave functions. At the same time, it is precisely this
the internal structure of ionic functions determines the effect of ion interference in the protein cavity in an alternating magnetic field in the absence of quantum transitions. Today, the ion interference mechanism predicts
polyextreme biological effects:
— modulated by magnitude/direction of the MP,
- magnetic vacuum,
— constant MP taking into account the proper rotations of ion-protein complexes,
— pulsed magnetic fields against the background of parallel constant magnetic fields,
— MP in the NMR frequency range taking into account the spin degrees of freedom of the iso-

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tops of ions,
— due to the interference of the states of a molecular group with a fixed axis of rotation — a molecular gyroscope,
- weak alternating electric fields,
— shift of the spectral peaks of the MBE during rotation of biological samples, see section 4.

Biological effects explained within the framework of the interference mechanism have been observed in various experiments. The formulas give dependence of the probability of dissociation of the ion-protein complex on the characteristics of the MP, the frequency of the variable component, the values and mutual orientation of the constant and variable components. Essential features spectra, the positions of the extrema, depend on the masses, charges, and magnetic moments of the participating ions. In most of the cases studied, calcium, magnesium, zinc, and hydrogen ions were found to be relevant.
less often potassium.

Many authors associate the biological action of magnetic fields with altered states of water [107, 290, 617, 115]. The change in states occurs as a result of the impact of external fields on water and is transmitted further to the biological level due to the participation of water in various metabolic reactions. It is currently unclear what exactly in liquid water could be the target of the MP action. It was assumed [107] that part calcium ions in water form hexaaqua complexes $[Ca(H_2O)_6]^{2+}$ with octahedral coordination of water molecules (by oxygen). Complexes, in turn, are closed in pentagonal dodecahedrons, the cavity size of which is 4.9–5.2 Å corresponds to the size of the complexes. This ensures the relative stability of the structures. The magnetic field shifts the equilibrium towards the binding of free calcium into complexes and, thus, affects biological signaling. In [617], based on the study of low-frequency spectra of water electrical conductivity, stable water-molecular associates with the property of memory for electromagnetic influence were discussed. Stable

structural changes in water were observed in [127] using luminescence spectra and were associated with the presence of various types of defects in water with characteristic radiation centers. Changes in biological activity water under the influence of a constant magnetic field was found in [446, 389], under the influence of radiation from a household television in [3]. Preliminary exposure of a physiological solution for several minutes to a constant magnetic field of several mT changed the physiological parameters of the nervous cells placed in such a solution [549]. In [290], the nuclear spins of water protons were considered as the primary targets of the magnetic field, and metastable

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The activity was associated with the orbital current states of protons in hexagonal water-molecular rings and deviation from the normal stoichiometric composition of water. The existence of such states can be verified in relatively simple experiments [23]. The memory effects of water during interaction with EMF were observed in [151] by

radio frequency spectra and associated with vibrations of hexagonal water-molecular ring associates. A generally accepted point view on the nature of memory carriers in liquid water and their interaction with EMF is not yet available.

They suggest the existence of long-range fields associated with the geometric property of space torsion [215], which can propagate independently and also accompany the propagation of electromagnetic fields. The scientific field of geometrization of physical fields has existed since the last century. The general object of new theories is so-called torsion fields. Mathematically, they are tensor fields fields that describe the curvature of space and the Ricci torsion, and not Cartan torsion, as in standard torsion theories. Known fundamental fields, their equations, arise here as some limits. Since energy is not an adequate characteristic of torsion fields, in particular, they do not obey the inverse square law, the concept of weakness or smallness of such fields is not defined.

It is possible that biological sensitivity to ultra-weak EMFs is associated with the spread of altered spatial geometry: weak Magnetic fields influence biological systems through the torsion fields they generate. We emphasize that this hypothesis is speculative; there are no reliable experiments confirming its reality. the specified fields. Their theoretical studies have their own difficulties [171].

3.2 Fundamental limit of sensitivity to EMF

A growing body of magnetobiological data demonstrates that MP levels of 1–10 ÿT and less can also affect biological processes. These data, schematically presented in Fig. 3.1, have significant interest. They do not agree with any of the proposed primary mechanisms of biological action of MPs and therefore raise the question of physical limitations that determine the possible the fundamental nature of the biological effects of ultraweak radiation

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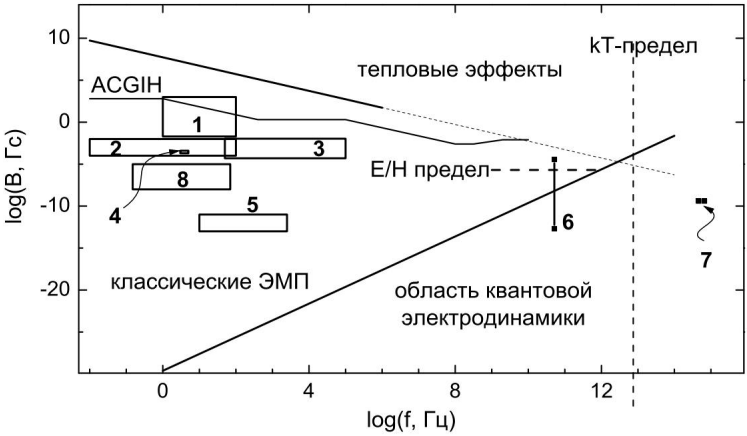


Fig. 3.1: Shows the various limits and regions of biological effects of EMF as a function of two variables, the EMF frequency f and the classical amplitude of its magnetic induction B. Explanations are given in the text.

lei.

The areas marked with numbers indicate the ranges of change of parameters of the following fields: 1 - low-frequency EMF used in most magnetobiological experiments; 2 - EMF of magnetic storms, which are known to correlate in time with exacerbations of cardiovascular diseases; 3 - background EMF generated by various household electrical equipment, television screens and computer monitors; 4 - MF causing changes in solutions of certain amino acids [144, 196]; 5 - magnetic fields

Tecno-AO devices, patent 93/00546 (France), presumably induced by radiation from video monitors and cell phones [730]; 6 — EMFs below the quantum electrodynamic limit, which cause a biological reaction in *E. coli* cell culture [635]; 7 — the limit of sensitivity of the human eye to EMF of the optical range; 8 - magnetic fields used for the treatment of certain diseases [489].

The figure also shows the theoretical limits associated with various mechanisms and descriptions of the bioeffects of EMF. The upper inclined line divides, very approximately, the areas of thermal and non-thermal effects. The lower inclined line is quantum-

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electrodynamic limit. It is natural to describe EMF in the classical way above this line. The stepped line is one of the known thresholds of safe values of EMF - given according to the version of the American Conference on Industrial Hygiene (ACGIH) [584]. The kT and thermal limits are well known. To the left of the dotted vertical

line separating the "paradoxical region", the quantum of energy of the electromagnetic field many orders of magnitude less than the characteristic energy of chemical transformations ÿ ÿT Many physicists, not specifically involved in the problem of magnetobiology, therefore believe that such fields are not capable of causing a biological reaction. Today, this point of view seems unjustifiably superficial, due to a multitude of

experimental facts that refute it. It is clear that in practice
the whole of electromagnetic biology lies in a “paradoxical area”.

The thermal limit has been repeatedly derived in scientific research and work on standardizing safe levels of EMF radiation,
see also section 1.4.1.

The dotted horizontal line in the area of relatively high
frequencies are defined with respect to the idealization of plane waves. Below
On this line, the influence of the electric component of the plane wave on the dynamics of the bound particle can be neglected, see section 1.4.3.

The quantum electrodynamic limit requires comment.
The interaction between EMF and matter is classified according to the types of description, classical or quantum, of both field and matter.
Most of the proposed primary mechanisms use the classical description of particles of matter interacting with a classical electromagnetic field, a wave field. Mechanisms explaining the bioeffects of electromagnetic fields based on the quantum description of ionic particles in the classical
EMFs are based on the semiclassical approximation. The conditions for the applicability of the classical description of EMFs are established by quantum electrodynamics: the populations of the quantum states of EMF oscillators
must be large enough compared to unity. This leads to a relationship that links frequency and classical amplitude.
the magnetic component of the EMF: H> ÿ c(f /c)2. This limit is shown by the lower line in the figure. As can be seen for low-frequency effects, in contrast to ultra-weak microwave radiation, it is permissible to use the classical description of the EMF using Maxwell's equations. However, in some cases, one can also speak of quanta of low-frequency EMF. The semi-classical approximation is sufficient to describe the bioeffects of low-frequency MF. However, the presence of bioeffects

EMF in area 6 does not exclude the involvement of quantum field mechanics.

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magnetoreception bases.

Apparently, the natural fundamental limit of sensitivity to low-frequency fields is associated with EM field quanta. The natural limitation on the electromagnetic sensitivity of biosystems, as well as any receiver of physical nature, should be

dictated by the general laws of quantum mechanics. All physical
The limitations proposed to date are based on *a priori* assumed primary mechanisms of reception, and not on the first physical
principles. Therefore, it would be interesting to obtain some estimates of the marginal sensitivities, albeit very approximate, but coming from general
physical laws.

The first thing worth noting is the incorrect formulation of the question about the minimum amplitude of the alternating magnetic field recorded by the receiver. The most general description of the interacting field and the idealized atom is the quantized electromagnetic field and the quantized
oscillator. A quantum of low-frequency electromagnetic field, initially delocalized in an indefinitely large volume, is absorbed by an atom-like
microscopic system in the process of reduction of the field wave function. In this case, the number of excitation quanta of the atom increases by one. The quantum-electrodynamic limit in Fig. 3.1 indicates approximately the boundary of the magnitude of the magnetic field, where the concept of the amplitude of the classical
The field loses its meaning. This boundary corresponds to several excitation quanta of the field oscillators in the quantum description.

In general, to characterize the sensitivity of the receiver
the adequate quantity is the energy flux p, that is, the number N of quanta ÿ absorbed by the system during the time T of its coherent interaction
actions with the field:

$$p = N\ddot{y}/T .$$

But in the area of applicability of the classical description this value is not
has an unambiguous connection with the amplitude of the field H, which indicates
the inapplicability of this concept in the sense of extreme sensitivity.
The constraints on the value of p follow from the fundamental relation
quantum mechanics between the change in the energy of a quantum system e and
time ÿ required to register this change

$$e\ddot{y} > .$$

In the case of recording N quanta, this relationship can be written as ÿ> 1/Nÿ, since e ÿ Nÿ.
However, the time of recording changes in
in any case, cannot exceed the time of coherent interaction
fields with an atomic system.

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In the case of low-frequency EMF, the time of coherent interaction is mainly the lifetime of the quantum state T determined by the features of the interaction with the thermostat. , Hence
the inequality T >ÿ> 1/Nÿ follows, that is, T> 1/Nÿ, which, after
substitution into the expression for p gives a simple estimate for the limit
sensitivity

$$p > /T^{2} . \qquad (3.1)$$

Thus, the limit of sensitivity to low-frequency EMF
is determined by the lifetime of the quantum state of the receiver target. For example, the spin states of protons in liquid water "live" for several seconds. The corresponding sensitivity limit is p ÿ
10ÿ19 W is close to the sensitivity limit of physical measuring instruments operating at room temperature. Let us recall that
limit (3.1) follows only from fundamental principles. The sensitivity of devices, including biophysical targets, also depends on the probability of their absorption of EMF quanta and will probably be significantly lower, and the sensitivity limit, accordingly, is significantly greater than (3.1). It is fundamental, however, that the probability

the absorption of EMF quanta is determined by a specific device
targets.

■ First principles of physics do not impose any limits on the maximum sensitivity. The microscopic structure of the biological receptor and the time of its coherent interaction with the EMF determine the level of sensitivity in each specific case. It is important,

that the time of coherent interaction can be quite large, due to the state of the living system, far from thermal equilibrium.
equilibrium.

3.2.1 Noise limits of sensitivity of biostructures to EMF

One of the phenomenological approaches to determining the maximum sensitivity of biosystems to EMF postulates that a biological EMF detector, whatever it may be, can be represented as an equivalent, in
in a sense, an electrical circuit or radio-technical structure consisting of resistors and capacitors. This is convenient, since the intrinsic electrical noise can then be easily estimated using the Nyquist formula. It is further argued that the putative biological detector, without having a priori information about the signal being detected,

is capable of distinguishing only a signal no less than its own noise. Thus

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Thus, the assessment of the sensitivity of a biological system is reduced to assessment of the level of intrinsic noise of the proposed detector.

In the simplest case, a biological detector is assigned complex impedance Z(ÿ) with active resistance R = (Z). Then the spectral density of the random emf is equal to

$$(2)\ddot{y} = 2\ddot{y}T\ R.$$

In this case, the conditions for the validity of the Nyquist formula are assumed to be fulfilled: ÿ ÿT c/ÿ, where ÿ is the size of the ÿdetector.

It is believed that biological tissues and biophysical structures do not have their own inductive resistance. The sometimes observed in measurements, the inductive component is caused by the current delay due to the inclusion of electrochemical processes [25]. Therefore, the reactive part of the impedance is determined by the capacitive resistance, inversely proportional to the frequency, (Z)=1/ÿC. Then the effective the detector bandwidth is ÿ ÿ 2ÿ/RC. The Nyquist formula gives in this band the mean square noise emf of the detector has been ^{2} =4ÿÿT /C.

repeatedly hypothesized that the molecular target EMFs are ion channels of biological membranes. Membranes, formed by phospholipids, have a thickness of about d ÿ 5 · 10ÿ7 cm and a permittivity of the order of ÿ ÿ 10. Since the capacitance of a membrane section with a radius of the order of the radius of the ion channel r ÿ 10ÿ7 cm is equal to C ÿ ÿr2/4d, then the noise emf, referred to the thickness membranes, that is, the noise electric field in the ion channel, has level

$$\text{Enoise}\ \ddot{y}\ \frac{1}{r}\ \sqrt{\ddot{y}\ddot{y}T/d}\ \ddot{y}\ 3 \cdot 10\ddot{y}3\ \text{units. GHS}\ \ddot{y}\ 100\ \text{V/m}.$$

Let us recall that the field induced by an alternating magnetic field of 50 Hz is 100 ÿT in a 1 cm sample near the solenoid axis is equal in order of magnitude to 0.1 mV/m. The reaction of biological systems to currents in tissues initiated by fields of 3–5 mV/m. Thus, limitations associated with noise do not allow a single channel to be a receptor of weak electric fields, within the framework of "radio engineering" performances.

Formally, the inversely proportional dependence of Enoise on the size r of the membrane region suggests that a detector represented by a comparatively larger region would be much more sensitive. There are some considerations about how such calculations could be linked to an assessment of the sensitivity of a hypothetical

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weak electric field detector in the form of a large ensemble of single channels or in the form of a single cell, see the work of Astumian, Weaver and Adair [254].

Another direction in the development of this topic is given by the work of Jangerman and Rosenblum [494], where it was suggested that the orientation of some elasmobranch fishes in the geomagnetic field is determined by the emf induced in large circuits, of the order of the transverse size of the fish, when the magnetic flux through the circuit changes. The electroreceptors of fishes have high sensitivity [32] and could, in their connection with electrical conducting circuits, explain the fact of magnetoreception.

According to [494], the stingray's electroreceptors have resistance
105 Ohm. Let us assume that the characteristic frequency associated with movement
The frequency band of the stingray, like the effective frequency band of the electroreceptor, is of the order of ÿ = 10 Hz, and the area of the conducting circuit is equal to S = 10 cm2. Then, equating the average noise and induced noise to each other
slopes of the EMF circuit, SÿB/c, it is easy to derive a relation for the threshold sensitivity to MF

$$B = \frac{c}{S}\sqrt{\frac{2kT\,R}{\ddot{y}}}\ \ddot{y}\ 10\ \ddot{y}T.$$

This figure does not contradict the hypothesis linking magnetoreception
these fish with the phenomenon of magnetic induction and electroreceptors. Also
it does not contradict the experimental data of Kalmijn [499].

Despite the apparent general nature of the estimates, the scope of their applicability is limited to mechanisms associated with the flow of current through
detector due to the additional, deterministic EMF of the signal. Indeed, if the signal were to modulate, for example, only
the detector's own resistance, no detection would occur. Mechanisms in which the rate of a chemical reaction changes under the influence of a signal also fall outside this scheme: this process has no electrical analogue. Mechanisms that provide amplitude windows for the efficiency of magnetic resonance also cannot be analyzed within the framework of this approach: linear electrical circuits, even

the most complex ones, being linear systems, have selective properties only with respect to frequency, but not to amplitudes
signals. On the other hand, the *ad hoc* introduction of additional nonlinear elements into equivalent electrical structures made
would make it impossible to apply the Nyquist formula. The fluctuation-dissipation theorem underlying the Nyquist formula is limited to systems with a linear response.

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It should be noted that the very possibility of representing a biological system as an electrical circuit requires justification. Pilla, Nasser and Kaufman [604] suggested that biological tissue can be represented as a linear one-dimensional chain of electrically connected single cells, each of which has an equivalent electrical circuit of resistors. Such a circuit, under certain conditions, allows overcome the noise limit, starting from fields of the order of 1 mV/m. However, On the one hand, reducing biological tissue to a one-dimensional chain is not quite convincing. On the other hand, the effects of weak EPs are also observed at the level of cellular systems outside of direct cell contact. So far there is no data that the calculations of the maximum sensitivity within this representations would be consistent not with the number, but with the experimental *curves.* Barnes [260] proposed to consider neurons, pyramidal cells of the cerebral cortex as a kind of radio-technical antenna phased arrays, equipped with amplifiers and filters. Such gratings would detect coherent signals induced by low-frequency external fields in the den- neurons against a background of thermal noise. However, no method for testing such a hypothesis has been proposed. Thus, there are many grounds for searching for alternative mechanisms not related to electrical currents, nonlinear mechanisms of biological reception of weak magnetic fields.

If we limit ourselves to the biological effects of the magnetic field at the level of the geomagnetic field, then the most important from the point of view of fundamental physics are two problems of an equally paradoxical nature: 1) the mechanism or the process of converting the magnetic field signal into a biochemical response, the energy scale ÿT of which is ten orders of magnitude greater than the quantum of magnetic field energy, and 2) why thermal fluctuations of the same scale ÿT do not destroy this conversion process. At first glance, the paradoxical nature of the second problem is much more noticeable, since the "obvious" The solution to the first problem is to accumulate the energy of the MP signal or to amplify it. Accordingly, the main attention was paid to solving the second problem. problems, and the transformation mechanism was chosen almost arbitrarily. However, the description of the "windowed" polyextreme spectra observed in the experiment depends on the transformation mechanism; it is this mechanism that determines the predictive power of the model. Therefore, Today there are no predictive models that solve both problems simultaneously, with the possible exception of [305]. At the same time, there have appeared predictive models [293, 297] that solve the first problem. This an important stage characterizing the state of theoretical research in the field of magnetobiology. The predictive power of such models

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ley means that the biological effects of weak magnetic fields, such as
important environmental factors become predictable.

Let us now consider in more detail some of the frequently proposed mechanisms
of the IBE. Criticism of such works seems, although
thankless but necessary activity.

There is some terminological ambiguity.
In the literature, the term “cyclotron resonance in magnetobiology” is often used to
refer to several essentially different models belonging to Libau.
In addition, these models are remembered almost every time they are found
MBE at the cyclotron frequency ÿc MP, missing the point that this
The combination of ion constants is related not only to cyclotron resonance, but also
to a number of other effects. On the other hand, judging by
In the literature, “parametric resonance in magnetobiology” is not associated
with a specific name, but with the specificity of mathematical equations, -
and therefore appeals to a variety of models, classical and quantum,
with and without potential forces, etc. However, we retain this terminology, paying
tribute to the established literary tradition, and we hope
that the reader can easily identify each of the following models in
within the framework of the objective classification proposed above. First, we will
consider the phenomenological models, then the macroscopic ones. Next
The most promising, microscopic, mechanisms of MBE will be considered.

3.3 Models based on chemical equations chemical kinetics

The equations of chemical kinetics are written for concentrations Ci(x,t)
substances entering into reactions:

$$\frac{\ddot{y}}{\ddot{y}tCi} = di\ddot{y}2Ci + \sum_i aiCi + \sum_{ik} bikCiCk + \dots , \qquad (3.2)$$

where ÿ2 is the Laplacian, di are the diffusion coefficients of molecules or other objects
of a given type, a, b, . . . are coefficients depending on
reaction rates, and through them, on external parameters. In a more general case,
the coefficients can also depend on the coordinates, representing
sources and sinks of reagents.

Even when the spatial distribution of the reactants is not taken into account, these
equations, especially for biochemical systems, represent complex nonlinear systems
of differential equations.

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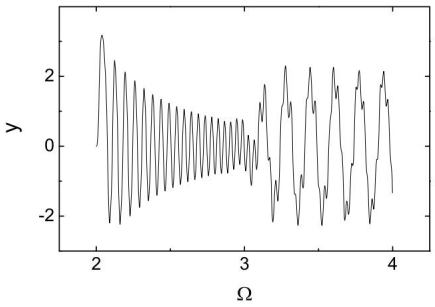


Fig. 3.2: Bifurcation of change stability of the Van oscillator der Pol when changing frequency exciting force.

such systems often have a rich set of possible types of solutions, including oscillatory ones, depending on the values of the parameters and initial conditions. The phase portrait of such systems can include several regions of "attraction" of the dynamic point. Once in such a region, the system performs an oscillatory motion in it, then There is, is in dynamic equilibrium, or tends toward stable static equilibrium. Without external control influences on parameters or variables, such systems, called polystable, are unable to transition to other regions of stability.
If the system is in a state close to unstable, that is, between areas of stability, then even minor controls or noise disturbances are capable of “switching” the system from one dynamic regime into another. So-called bifurcations occur.

Under the condition ÿCi/ÿt =0, that is, in the stationary regime, some solutions (3.2) represent the so-called dissipative structures. This non-uniform distributions of reactant densities that arise during the presence of energy or mass flows through the systems under consideration, in this case open ones. The existence of dissipative structures, a kind of patterns, spatial structures, also depends from a combination of parameters and can undergo bifurcations when the parameters vary.

As an example, Fig. 3.2 shows the coordinate dependence Van der Pol oscillator excited by an external harmonic force

$$y \ddot{y} (1 \ddot{y} y2)y + y = 10 \sin(\ddot{y}t)$$

from the excitation frequency, which changed smoothly over time. It is visible the emergence of a qualitatively different dynamic regime with a two-frequency spectrum at a certain frequency value.

Nowadays, there are many known applications of the prescribed

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here and similar equations for the description and study of not only chemical, but also biological and social processes. These materials are found, for example, in the monographs of Ivanitsky, Krinsky and Selkov [95], Prigogine [618], Chernavsky [208], in the review by Medvinsky, Petrovsky and others [200].

When applied to the problem of magnetobiology, most authors is based on the assumption that EMF is capable of causing a change in the rate of one or more biochemical reactions involved into the system under study. It is further shown that the system *can* exist in a region close to an unstable regime, and various dynamics of chemical processes arising at a small variations of certain parameters. If it turns out that the character dynamics is close to what is observed in the experiment, then this is the basis for concluding that the experimental system is indeed in an unstable equilibrium, and the EMF acts precisely on that link of biochemical transformations that was subject to variation tions.

It is obvious that the physical or biophysical processes of the primary MP receptions fall outside this scheme. The relationship between the reaction rate constant, for example, and the magnitude of the MP is usually postulated as a linear relationship. dependencies. Here one could compare with the experiment as both frequency and amplitude spectra of the response of a dynamic system to the disturbance of a constant potentially sensitive to EMF. However, the value of such a comparison is still not absolute. The process of primary reception is also not prohibited from having some frequency and amplitude selectivity. In view of this, the hope is to obtain well-matched responses to EMF in the experiment and in models based on The correspondence between the primary and secondary processes based on the equations of chemical kinetics is quite small. Even if a correspondence is obtained, it is difficult to interpret. There are works presenting “end-to-end” models, where the primary reception process with its characteristics is built into the kinetic system. Grundler and Kaiser [568] and Kaiser [497] considered several such mechanisms, making certain assumptions about the properties of the primary process. The interaction of the magnetic field with moving objects is also considered. spatial structures such as autowaves in excitable media, for example, spiral waves [723], which are also solutions special cases of equation (3.2).

Chemical kinetic equations with singular solutions were used by Plyusnina, Riznichenko et al. in [51] to describe near-membrane processes in EMFs. The Eichwald and Kaiser model [407] of repulsion

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comes from experiments on the influence of low-frequency fields on cells immune system, in particular T-lymphocytes. This work discusses the possibility that the external field affects the transmission process signals (signal transduction) between activated receptors on cell membrane and G proteins. It has been shown that depending on a specific combination of intracellular biochemical and external physical factors can give rise to completely different forms
We have responses.

The number and variety of models in this class is great. Search scheme MP targets based on the study of responses of nonlinear systems are quite Kaiser [497] and Galvanovskis and Sandblom conducted successively [444]. In [444], the spectrum of intracellular oscillations of the concentration of Ca2+ ions caused by an external stimulus under conditions of periodic modulation of the rate of one of the intracellular reactions involving calcium was investigated. For mathematical modeling of Ca2+ oscillations used a system of ordinary nonlinear differential equations equations proposed in [449]. It was shown that the system response, expressed as the total spectral power of oscillations, has a complex character depending on the frequency and amplitude of the modulating signal. Frequency windows of the effect arose at a characteristic natural frequency of oscillations (ÿ 0.01 Hz) and, smaller in magnitude, on its harmonics. The emergence of an amplitude window was also noted. The authors varied all the parameters of the system in order to determine the most sensitive point in the reaction system. It turned out that that this is a reaction of calcium release into the cell from the calcium bound in intracellular proteins state.

Let us emphasize the value of models based on chemical kinetics. In the process of developing and comparing models with experiments, the most sensitive points of biochemical systems are found. the search for primary mechanisms is facilitated, since the potential circle reactions of those sensitive to EMF become more definite.

3.4 Models of the biological action of weak electric fields

One possible scenario for the effect of low-frequency magnetic fields on a biological system is that the magnetic field induces an alternating electric field in the tissue. This, in turn, causes eddy currents and electrochemical phenomena. Frequency- and amplitude-selective action

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the effect of external weak variables of the EP is a problem in itself
To describe the corresponding mechanisms, equations of chemical kinetics are used, in which the constants of some reactions, characterized by a relatively large change in the electric dipole moment, are assumed to depend on the EF strength.

Usually, when assessing the effect of a weak EP on a cell, we proceed from the additional potential on the surface of the cell placed in the EP.
In model problems, spherical or cylindrical objects are considered dielectrics placed in an external field. It is known that the potential
The EP E in a spherical system coinciding with the center of the dielectric ball has the form, see, for example, [123],

$$ÿ = ÿEr(1 ÿ A/r3) ,$$

where the constant A is determined from the conditions on the boundary of the sphere. On the surface of a sphere of radius R, or a cylinder, see Appendix 6.4,

$$ÿsphere = ÿER \quad \frac{3ÿ}{2ÿ + ÿi} \quad ,ÿcyl = ÿER \quad \frac{2ÿ}{ÿ + ÿi} \quad , \qquad (3.3)$$

where ÿ and ÿi are the dielectric constants of the medium and the modeled object. Since usually ÿ ÿ 80 and ÿi ÿ 3, 1 then for additional potential on the ball we obtain the expression

$$ÿ ÿÿ1.5 ER \cos ÿ, \qquad (3.4)$$

which is often used in specialized literature, see, for example, [712].

In addition, the bilayer cell membrane carries a large charge, negative on the inner membrane, which creates
transmembrane potential difference Um ÿ 70 mV. It is caused by the action of membrane pumps-enzymes that push ions
against their concentration gradient. Additional potential difference on the cell surface in opposite directions in the field
points follows from (3.4) and is equal to 3ER. Since the conductivity of the intracellular plasma is large compared to the conductivity of the membrane, It is believed that this potential difference occurs only on two opposite sections of the membrane, and thus, the additional EP

1For precise data on the dielectric parameters of biological cells and tissues, see in the review [557]. The physical and electrical parameters of the tissues are given, for example, in work by Misakyan, Sheppard, et al. [312]. For a brief summary of the electrical parameters, see Appendix 6.5.

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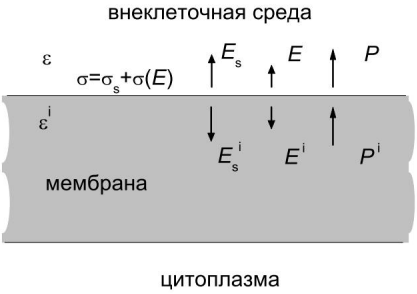


Fig. 3.3: Fields and polarizations on the outer surface of the membrane. The surface charge density is formed by foreign and polarization charges.

inside the membrane, induced by the external field, is R/2d times greater external.2 On one side of the cell, the transmembrane potential increases, on the other it decreases. The relative magnitude of the change, as
It is easy to calculate that for a cell of size R ÿ 10 µm in a field of 1 V/m it is equal to on

$$\frac{3ER}{2Um} \text{ ÿ } 10\text{ÿ}4 . \qquad (3.5)$$

The smallness of this value also poses a problem in electromagnetic biology. It's unclear how such small changes can alter membrane processes.

The situation is actually even more dramatic, as there are facts of biological reception of fields of the order of 1 mV/m. In addition, the formula (3.4) itself is hardly valid in assessing the change in the potential of a hollow structure, since it was obtained for a solid dielectric. Not complicating matters with spherical symmetry, which in this case introduces only an insignificant coefficient of the order of unity into the result, the cell is more easily modeled by a rectangular box filled with cytoplasm with dielectric properties similar to those of the intercellular solution. On the surface of the box membrane there are foreign charges provided by pump proteins, as well as charges due to polarization by an external electric field E. Surface density

2This statement, often made in papers on the effects of EP on biological cells, see, for example, *Bioelectromagnetics, 21(4):325, 2000,* is based on a mistaken disregard thermal effects and dielectric properties of the intracellular environment. The conductivity of the cytoplasm is due to free ions, that is, well-localized charge carriers. The energy of the thermal scale is much greater than the energy of charge displacement q per cell length in an external EF not exceeding 1 kV/m: ÿT qÿ. Therefore, thermal diffusion of free ions prevents the redistribution of ions and effective screening of the field inside the cell. Consequently, the potential drop occurs, mainly due to the dielectric polarization of the cytoplasm, and its conductivity can be neglected.

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The number of field-induced charges is equal to the difference in polarization of the medium on the inner and outer sides of the membrane surface [123], see Fig. 3.3,

$$ÿ(E)= Pi ÿ P.$$

Since we consider the polarization effects in the linear approximation, the polarization charge density can be found by setting
temporary absence of extraneous charges. In this case, the relation $ÿE = ÿi Ei$ is satisfied at the boundary of the dielectrics . Using also the equality $4ÿP =(ÿ ÿ 1)E$ on both sides of the membrane, we find

$$4ÿÿ(E)= ÿi Ei ÿ Ei ÿ ÿE + E = (1 ÿ ÿ/ÿi)E.$$

The surface charge density is related to the transmembrane potential by the relation of a flat capacitor

$$Um(E)=4ÿ[ÿs + ÿ(E)]d/ÿi ,$$

where d ÿ 5 nm is the thickness of the bimembrane. From here we find the change $ÿUm(E)$ of the transmembrane potential in relation to its value in
absence of field $Um(0) = Um$:

$$\frac{ÿUm(E)}{Um} = 1 ÿ ÿi \quad \frac{ÿ}{} \quad \frac{dE}{ÿi\ Um} ÿ\ 10ÿ6 \quad ,$$

that is, two orders of magnitude less than (3.5).

The relation (3.4) was used, for example, by Astumian, Weaver and Adair [254] They proposed a hypothetical mechanism illustrating the effect of an alternating electric field on biological
cell. This mechanism has neither frequency nor amplitude selectivity. Let's consider the idea itself, which will help clarify
the prospect of its use.

The membrane channels of the cell can be either in an open or closed state, Fig. 3.4. This point of view is substantiated by experimental observations of discrete changes in the conductivity of single protein channels. In thermodynamic equilibrium, in
under Boltzmann statistics, the channel probability ratio
be in open and closed states equally

$$p ÿ popen/pclose = exp(ÿU/ÿT) . \qquad (3.6)$$

If an external electric field causes a change in the potential difference
cials according to the ratio

$$U = U0 + ÿU \quad ,$$

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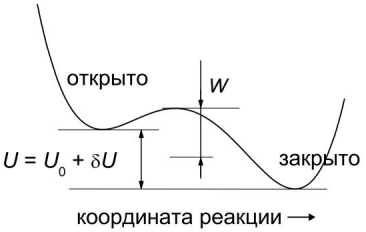


Fig. 3.4: Dependence of the free energy of the channel protein on generalized coordinate. Stable- The most obvious are open and closed. hidden state.

then the probability ratio can be represented as a power series
small parameter x = ÿU/U0. Taking into account the notation ÿ = U0/ÿT, we have

$$p(x)= eÿeÿx = p(0) + p\,(0)x + px2/2+ ...$$

The change in p on average over time is obviously associated only with the square of x-specific member:

$$ÿp = \frac{1}{2}ÿ2eÿ\overline{x2}\,.$$

The assumption was that a deviation of p from the equilibrium value could lead to an increase in the rate of transport of oxidant molecules by the protein into the cell and to the accumulation of damage as a result
DNA for quite a long time.

The value of U0 in Fig. 3.4 corresponds to the transmembrane potential of the cell with a transferred charge value of several units. Then
ÿU is the change in this potential in an external electric field.
As we determined above, the amplitude of the relative change in the transmembrane potential in a field of 1 V/m is equal in order of magnitude to 10ÿ6.
Therefore, the average value of the square x2 over time is

$$\overline{x2} ÿ\ 2 \frac{1}{} 10ÿ12 \quad ,$$

where x ÿ cos ÿt is assumed. On the other hand, the value of ÿ for physiological temperatures is approximately equal to eight. From this we obtain
assessment of the constant component in the change in the value of p in the variable nom field

$$ÿp ÿ\ 10ÿ6–10ÿ8\ .$$

The smallness of this value indicates that its use is questionable.
of this idea. According to the calculations of the authors of the idea, the specified level of the alternating field could lead to a biological effect. However,

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several idealizations made during the calculations are significant
reduce the value of such a conclusion. The prediction of the mechanism is
quadratic dependence of the effect on the amplitude of the electric field.

The mechanism of action of EP on biological systems, cells, possessing
frequency selectivity, was developed in a series of works,
a review of which is given in the article by Tsong [699]. The idea of the mechanism is
is that if the conformational states A and B of the molecule have a dipole electric moment,
then the chemical equilibrium of these
forms

$$A \underset{k\ddot{y}1}{\overset{k1}{\rightleftharpoons}} B$$

can be shifted in the external EP E in accordance with the equation
Van't Hoff type equation

$$[\ddot{y} \ln K/\ddot{y}E]_{P, V, T} = M/RT , \qquad (3.7)$$

where K = k1/kÿ1 is the equilibrium constant, M is the difference in the molar
dipole electric moments of states A and B, R is the gas
constant. This applies to the conformational states, active and inactive, of an
ATPase-type enzyme catalyzing the reaction
membrane transport of the substrate into the cell. Frequency selectivity is postulated and is
a consequence of the frequency correspondence
external field and the relaxation rates of the reactants. There is no amplitude
selectivity in the model, although a review of experiments on ATPase
reactions in strong EF, ÿ 0.5–5 kV/m, available in this work, shows the
presence of a maximum in the region of 2 kV/m. A qualitative result,
obtained by computer modeling with some combinations of several
parameters describing enzymatic transport
show that the EP can lead to a constant, on average, pumping of the substrate through the
membrane. Theoretical estimates of the effective field values are not provided. Such an
estimate follows from equation (3.7), rewritten in a normalized form per molecule:

$$K/K0 = \exp \frac{\ddot{y}D\ E}{kT} ,$$

where ÿD is the difference between the dipole moments of the molecule in states A and
B. Sometimes this value is associated with the movement of several
elementary charges over a distance of the order of the membrane thickness d, then
there is ÿD ÿ 10ed. Then, at physiological temperature, in the field E ÿ

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1 kV/m, we obtain ÿK/K0 ÿ 10ÿ3. Apparently, the model's potential for explaining the biological effects of strong electric fields. The weak point here is the lack of the predictive power of the model, the complexity of its experimental verification. In particular, the authors did not predict the dependence of the effect for any other changed conditions of the electromagnetic environment new items.

In the work [699] another mechanism was proposed to explain the biological reception of weak, of the order of ÿV/m, variable EP. In this The mechanism assumes that the height of the barrier W separating the active and inactive states of the membrane protein-enzyme in the reaction Michaelis-Menten type, see Fig. 3.4, changes in concert with the external electric field. Frequency selectivity is postulated here, and its nature is associated with high-quality oscillations of a charged group of atoms inside the protein, induced by the external field.
These oscillations lead to modulation of the barrier height. Obviously, here The game is not about changing the probabilities of states, but about changing the rates of transition between these states. According to the theory of absolute reaction rates, the rate constant of the forward and reverse reactions can be written as follows:

$$k\pm 1 = k0 \exp \quad \frac{\ddot{y}W \pm U/2}{kT} \quad .$$

Due to the nonlinear exponential dependence of the transition rate constants on the barrier height, a nonzero, on average over time, contribution appears, caused by the external variable EP. The last expression is completely analogous to (3.6), from which we conclude that the relative change in the reaction rate is of the same order as the relative change in the equilibrium constant, that is, small. This mechanism

does not have amplitude selectivity. In addition, quantitative estimates were based on a number of model assumptions. The main one of them consisted of a statement that was questionable from a physical point of view, that the external EP can be enhanced by the plasma membrane, so that the change in field induced inside the membrane is approximately in Rcell/dmembr times more than the original external EP. Utilization of this mechanism in the processes of biological reception of weak electrical fields remains in question, since there are no special experiments for The mechanism was not tested.

Markin, Liu et al. [487] proposed an "electroconformational coupling" model that predicts not only the frequency but also the amplitude

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tight window. The model is based on the fact that both the state of the ion in the membrane transporter protein and the state of the transporter itself—
open inward or outward, depend on the electric field and are thermally activated processes. The interaction of these
processes leads to the emergence of an amplitude window. Frequency window
is caused by relaxation processes, as in [699]. The amplitude
The window is determined to be around 2 kV/m for the (Na,K)-ATPase of human erythrocytes. This is too large to try to fit the model to
explanations of frequency- and amplitude-selective bioreception of weak electric fields, such as fields induced in biological tissue by low-frequency magnetic fields.

Weaver and Astumian [712] estimate the ultimate sensitivity
cellular system to the electric field, assuming that the reception
EP is mediated by a process similar to the mechanisms discussed above. This process depends on the transmembrane difference.
potentials. Therefore, the maximum sensitivity could correspond, according to the authors' assumption, to noise fluctuations in the transmembrane potential difference. To estimate the latter, the Nyquist formula was used, see, for example, [126]. Regarding the validity of

A remark must be made regarding the use of this formula. The formula follows from the fluctuation-dissipation theorem for generalized susceptibilities *of linear* systems. Such a linear system in
in particular is the active electrical resistance. The current in the circuit,
reaction to an external electric field, associated with the field strength
linear dependence. The most important electrical property of the plasma membrane is its significant nonlinearity. It is this property that ensures the emergence of the transmembrane potential, the basis for the processes of nervous excitability. It must be recognized that in this case the general physical laws of linear

responses were used beyond their applicability. At least
At least, there needs to be a justification for such a strong idealization.

Other electrochemical mechanisms of cellular reception of electric fields based on the phenomena of electrophoresis, electroosmosis, redistribution of receptors and channels on the surface of cells
membranes are discussed by Robinson in his review [637].

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3.5 Stochastic resonance in magnetobiology

The need to take into account thermal disturbances of the environment in theoretical models of MBE is undeniable. However, there are still no models in which consistent consideration of the thermostat's influence would not destroy the desired effect of a weak magnetic field. Thermal disturbances of the environment manifest themselves as random forces acting on the intended target. Magnetic fields, most often charged particles. The search for subtle features of the behavior of dynamic systems in the presence of random forces that facilitate the preservation and transformation of a weak magnetic field signal to the level of a biochemical response continues. In fact, these studies touch upon the very essence of the so-called "kT problem."

Today, several areas of research can be identified in this region, where thermal noise is taken into account explicitly as stationary a random process of one spectrum or another. It seems obvious, that the application of methods of equilibrium thermodynamics or statistical physics is not capable of leading to the desired results. Research is focused primarily in the field of dynamic systems with quasi-chaotic behavior.

3.5.1 Stochastic resonance

Benzi, Sutera and Vulpiani in their work [279] proposed to call stochastic resonance (SR) a phenomenon that consists in a relatively a strong redistribution of the power spectrum of the dynamic variable of a nonlinear multistable system under the influence of a weak deterministic component against a background of additive noise under certain resonant conditions. Like atomic parametric resonance, stochastic resonance is not a resonance in the sense of an increase in response when adjusting the frequency of the control signal to the natural frequency of the system. The analogy is that the signal-to-noise ratio at the output of the system is maximum when adjusting the noise level in the input signal is reduced to a certain value.

Stochastic resonance (SR) is known in systems described by differential equations of the first order. For mechanical This corresponds to overdamped motion in the system, as a result of which inertial forces are not manifested. In this case, the equations do not contain accelerations, and the rates of change of coordinates are proportional

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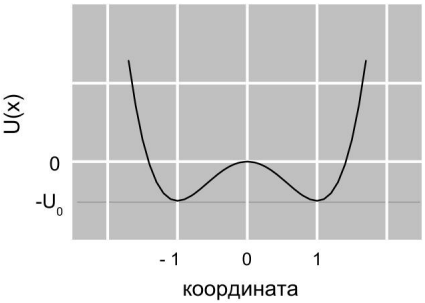


Fig. 3.5: The simplest double-well potential that ensures bi-stability of the dynamic system stems.

acting forces. If we consider the motion of one particle, then the equation has the form

$$x\ddot{y} = \ddot{y} \quad \frac{\ddot{y}}{\ddot{y}xU(x, t) + \ddot{y}\, D\ddot{y}(t)}, \qquad (3.8)$$

where ÿ is a random process, which is usually assumed to be ÿ-correlated, with zero mathematical expectation, D is the variance of the random force acting on a particle. The case where the potential function U(x, t) corresponds to the motion of a particle in a double-well is studied in detail. potential under the action of a regular harmonic force

$$U(x, t) = U0\, \ddot{y}2x2 + x4\, \ddot{y}\, U1x \cos(\ddot{y}t) .$$

The constant part of the potential is shown in Fig. 3.5. From (3.8) we obtain

$$x\ddot{y} = 4U0x(1\, \ddot{y}\, x2) + U1 \cos(\ddot{y}t) + \ddot{y}\, D\ddot{y}(t) . \qquad (3.9)$$

Computer modeling of equation (3.9) for illustrative purposes is not difficult. We performed our own calculations. The parameters of the equation were chosen as follows: U0 = 1, U1 = 1, ÿ = 0.1. Random The process ÿ(t) was modeled by a sequence of normally distributed, practically uncorrelated numbers with zero mathematical expectation and unit variance. The Runge-Kutta method was used to calculate the particle coordinates at 8192 points with a time step

t = 0.1. The corresponding spectra were obtained by fast Fourier transform. The amplitude of the spectral density S of the signal was determined by averaging the height of the spectral peak at a frequency of ÿ = 0.1 over six spectrum realizations. Different realizations were obtained by repeating the calculations with different input points for the random generator. ny numbers.

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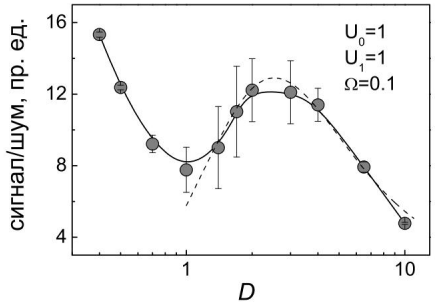


Fig. 3.6: Signal-to-noise ratio in the displacement spectrum particles under the action of harmonic force at different noise levels. Computer modeling dynamics (3.9).

The dependence of the signal-to-noise ratio on the noise intensity D is shown in Fig. 3.6. It has a characteristic local maximum at some level of noise density and is consistent with known results. For example, McNamara and Wiesenfeld [566] conducted more accurate Calculations: the local maximum was several times higher. This behavior of the curve is easily understood from Fig. 3.7.

At a fixed level of deterministic periodic force, insufficient for the particle to cross the barrier, it will be located all the time in one of the potential wells if the noise level is small (Fig. 3.7, top left). In this case, the amplitude of the particle's displacements is, on average, constant. As the noise intensity D decreases, the signal-to-noise ratio will obviously increase proportionally to Dÿ1, as in the left part of the curve in Fig. 3.6.

As the noise intensity increases, the particle can sometimes jump from hole to hole when under the action of a deterministic force it is shifted towards the barrier, and some of the random noise pulses, turns out to be quite large and is also directed towards the barrier (Fig. 3.7 top right). In this case, a correlation arises between the deterministic periodic force and the random transitions of the particle from well to well. The amplitude of such shifts, as can be seen, is significantly greater than shifts within a single well. This leads to an increase in the signal-correlated component in the shift spectrum.

This component on average reaches a maximum at a certain (resonant) noise level, when practically every half-period of the action of a regular force is accompanied by the transition of a particle from a well to pit (Fig. 3.7 bottom left).

The subsequent increase in noise no longer leads to a noticeable increase in the average amplitude of displacements, therefore the dependence of the signal-to-noise ratio again becomes inversely proportional to the noise density ÿ Dÿ1 (Fig. 3.7 bottom right). This corresponds to the right side of the dependence,

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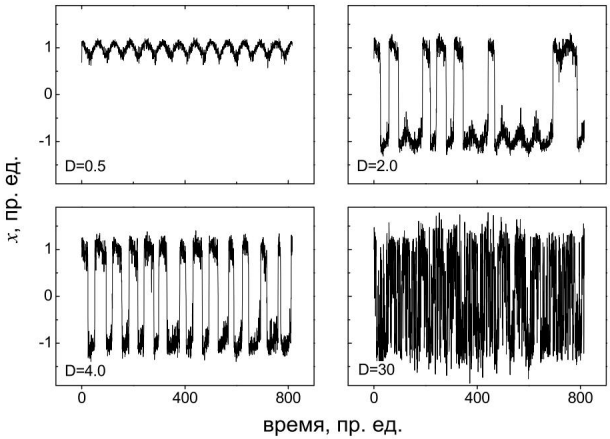


Fig. 3.7: Displacements of the coordinate of an overdamped particle in a double-well potential under the action of a harmonic force and a random force different levels of D.

shown in Fig. 3.6.

It turned out that stochastic resonance is a more general phenomenon, which is illustrated by a bistable system. In particular, it is observed under single-well conditions if the combined effect of the signal and noise, which disturbs the system from equilibrium and exceeds a certain threshold, triggers some other process. An example is the activation of a neuron by the combined action of a signal and fluctuations in the concentration of a neurotransmitter.

The middle section of the curve in Fig. 3.6, where an increase in input noise leads to an improvement in the signal-to-noise ratio at the system output, is the subject of much discussion. Stochastic resonance was observed in artificial systems with noise, such as the Schmitt trigger, ring bistable laser, superconducting quantum interferometer and others, a review of which is given in the work of Wiesenfeld and Moss [721].

They discuss the possibility of describing some natural phenomena, in particular, biological ones, using the laws of stochastic resonance. Attention is paid to the fact that relatively weak biological signals can lead to significant changes in the behavior of a dynamic system against the background of various, and relatively strong, disturbing factors - under conditions

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stochastic resonance. In [721] it is reported that the response of mechanoreceptor cells of the crayfish to an acoustic stimulus in the form of a subthreshold signal mixed with Gaussian noise satisfied the dependence of the type shown in Fig. 3.6.

3.5.2 Increasing the signal-to-noise ratio

It is believed that all biological sensory systems are threshold devices to one degree or another. Therefore, the assumption that magnetoreception is based on a stochastic resonance mechanism is entirely justified. The detection efficiency of weak magnetic resonance signals can be increased by the influence of noise factors.

A theoretical consideration of various models of stochastic resonance gives an approximate formula for the dependence of the signal-to-noise ratio R on the noise level D in the region of the maximum

$$R \ddot{y} \quad \frac{U1}{D}^{2} \exp \ddot{y}2 \quad \frac{U0}{D} \quad . \tag{3.10}$$

The formula is derived under the assumption that the output signal occurs only when a particle transitions from well to well or only when a certain threshold is reached. This means that the formula only approximately describes the rapid increase in R and its subsequent decline with decreasing D (the dotted line in Figure 3.6) and does not describe the subsequent increase on the left side of the figure, which is insignificant for applications. This is sufficient for analysis.

We are interested in how much the signal-to-noise ratio can increase with increasing noise D. The maximum value of R, for fixed U0, U1, according to (3.10) is

$$Rmax = \quad \frac{U1}{U0}^{2} \quad e\ddot{y}2$$

and is achieved under the condition of *an optimal* noise level

$$D = U0 \, . \tag{3.11}$$

As D decreases, the signal-to-noise ratio drops, theoretically, to zero.
la:

$$Rmin = \lim_{D\ddot{y}0} \quad R = 0 \, .$$

It would seem that one could achieve an arbitrarily large signal "gain" K = Rmax/Rmin at the expense of noise. However, this is not the case for the following reasons.

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At low noise levels D, the probability of transition W from pit to pit is becomes exponentially small. This is what leads to arbitrarily small values of R. At the same time, observing such rare transitions requires an exponentially large time. Therefore, small values of D have no practical meaning.

We obtain a reasonable estimate of the real gain K from the formula for average time to first barrier crossing [358]

$$ÿ = Wÿ1 = \exp\left(\frac{2U0}{D}\right), \qquad (3.12)$$

where ÿ is dimensionless and expressed in units of the system's relaxation time scale. The quantities U0, D, and U1, as already assumed when writing equation (3.9), are also dimensionless.

Let's say a biological receptor detects a subthreshold signal at some optimal noise level D = U0 over time t(D). Let's say, for example, that it is designed in such a way that about N intersections are required for the receptor to react to the appearance of a signal.

$$t(D) = Nÿ(D) .$$

At a lower noise level, the D receptor, under certain ideal conditions, conditions, would have detected the signal in a longer time t(D)= Nÿ(D). It must be taken into account that the physiological or biochemical readiness of the receptor to detect a signal is maintained only for some characteristic time T the signal at a · If T <t(D), then detect given noise level in the experiment will not be possible. Accordingly, there will be no estimate for the signal-to-noise ratio. Thus, The "lifetime" of the receptor T determines the lower limit of noise in the experiment, when the signal-to-noise ratio still has practical meaning. For the purposes of the estimates, we assume that the lifetime of the receptor T is n orders of magnitude greater than the time of its optimal (that is, at D = U0) reaction t(D). From which it immediately follows

$$\frac{ÿ(D)}{ÿ(D)} = 10n . \qquad (3.13)$$

Using (3.10), (3.12), the relationship for the desired value of the greatest gain can be written as follows:

$$K = \frac{R(D)}{R(D)} = \frac{\ln ÿ(D)}{\ln ÿ(D)}^2 \frac{ÿ(D)}{ÿ(D)} .$$

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Taking into account (3.13) and taking into account the equality ÿ(D)= ÿ(U0)= e2, let's write down the last equality

$$K = \frac{\ln ÿ(D)}{\ln ÿ(D) + n \ln 102} \quad 10n = \frac{10n}{(1 + 1.15\, n)2} . \qquad (3.14)$$

Thus, if, for example, the lifetime of a receptor exceeds its reaction time by n = 1; 2; 3 or 4 orders of magnitude, then the greatest enhancement will be about K ÿ 2; 9; 50 and 320, respectively. In decibels3 these the values are 3, 9.5, 17 and 25.

Note that the lifetime of the receptor implies preservation in during this time of biochemical conditions that ensure reception. Homeostasis in the body, that is, the relative constancy of its functions, composition, etc., exists only as *a dynamic* equilibrium. Therefore, it is fair to assume that some receptors are destroyed by metabolic processes or stop working, while others, on the contrary, begin. Considering that for most receptors the reaction time is a fraction of a second, the value of n does not exceed n = 3; 4 looks plausible; in this case, the lifetime of the receptors would be about minutes.

In experiments, slightly smaller gains are observed. The signal-to-noise ratio dependences on the noise level, constructed from the results of various relevant experiments and numerical models of stochastic resonance, show the following (data are presented in [566] and [721] and summarize the results of several studies). In
In the ring laser, the gain was 11 dB; in the experiment with cancer mechanoreceptors, 6 dB; in computer models: double-well potential, 4 dB; neuron, 7 dB; SQUID, 12 dB; trigger, 10 dB.
In our own two-hole model, we obtained an increase of 1.5 times, that is, about 2 dB, Fig. 3.6.

■ The signal-to-noise ratio in most systems studied to date increased under the influence of noise by an average of only order. To identify the fact of greater amplification under the influence of noise It is necessary to be able to reduce noise and increase observation time. This possibility is not always available in a real experiment.

3Decibel, dB, is one tenth of the decimal logarithm of the ratio of two quantities.

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3.5.3 Limitations on the magnitude of the detectable signal Ia

Obviously, after amplification, the signal-to-noise ratio should be close to unity in order of magnitude. Otherwise, we must assume the presence of some additional, higher-level system that would ensure signal separation from noise.

There are certain limitations on the magnitude of the deterministic signal U1 to be "amplified". On the one hand, the signal should not be large. Otherwise, the signal, regardless of
noise, sufficient for the particle to pass through the barrier. This happens, when the potential is at maximum signal

$$U(x)= U0(ÿ2x2 + x4) ÿ U1x$$

has only one extremum, the minimum. That is, the equation U_x =0 name- there is a unique solution. From this it is easy to obtain that the upper bound amplified signals are $U1 = 8U0/ 3 ÿ 3$.

On the other hand, detecting a weak signal against a background of noise implies its "accumulation" over a certain sufficient period of time. time. In numerical modeling, for example, this corresponds to averaging of many, say m, realizations of the output signal power spectra, when the noise wing of the spectrum is smoothed out and ÿ-shaped the signal peak in the spectrum becomes noticeable. The same thing happens when the time interval for observing a random (ergodic) system increases by a factor of m. In an experiment or in a biological system, as already mentioned, this time, T, is limited for one reason or another. What imposes restrictions on the magnitude of the weak signal, which is still can be detected.

We obtain a rough, but sufficient for our purposes, estimate of the minimum detectable signal. In the presence of a signal, the average time the first crossing of the barrier becomes equal to 4

$$ÿ ÿ \exp [2(U0 + U1 \cos ÿt)/D] .$$

The change in this time, that is, the difference ÿ of the quantities $ÿ(U0) ÿ \exp[2U0/D]$ and $ÿ(U0 + U1) ÿ \exp[2(U0 + U1)/D]$ leads to the detection of a signal. This difference is revealed only when the system transitions from pit into pit. In order to be able to judge the presence of this difference, that is, about

4This is true if the signal changes slowly enough and does not violate the transition statistics (adiabatic approximation), that is, the frequency ÿ and the relaxation time systems tr are related by the relation $ÿ < 1/tr$.

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presence of a signal, it must be reproduced a certain sufficient number of times, say, in n transitions. In this case, n ÿ corresponded
would be the characteristic scale of the process, that is, n[ÿ(U0 + U1) ÿ ÿ(U0)] = ÿ(U0). From here we obtain

$$n\,\frac{d\ddot{y}(U0)}{dU0}\,U1 = \ddot{y}(U0)\,, \qquad \text{that is, } U1 = \frac{D}{2n}\,.$$

To detect a small signal, you need to accumulate a sufficient number
transitions n, but it is limited by the receptor lifetime: nÿ(U0) <
T . From here we obtain the boundary of detectable signals in the region of optimal noise D = U0,
U1 ÿ U0ÿ(U0)/2T. Thus, detectable
My signals fall within the range

$$\frac{D\ddot{y}(D)}{2T} < U1 < \frac{8}{3\ddot{y}3} D. \qquad (3.15)$$

■ Within the framework of the above considerations about the bioreceptor lifetime, the minimum detectable signals could be values of (10ÿ1–10ÿ4)D. Let us recall that the signal levels U1 ÿ D ÿ U0
corresponds to the maximum signal-to-noise ratio.

Stochastic resonance and microparticles

Let us note one more limiting circumstance. Stochastic
resonance is observed in dynamic systems described by first-order differential equations. This means that the particle, the supposed target of the magnetic field, is overdamped. That is, the forces
"Viscous friction" forces must be much greater than inertial forces. For a microscopic particle, such friction is realized at the same degrees
freedom of the environment, as well as thermal noise. Repeatedly taking into account the same factor, random displacements of particles interacting with the target, in the form of phenomenological attenuation and in the form of a disturbing force, is inconsistent. The transition to the quantum dynamics of a microparticle in this sense does not offer new possibilities. The Hamiltonian
particles includes inertial terms - terms containing operators of double differentiation with respect to coordinates. Introduction of damping,
necessary for stochastic resonance, is associated with the same
as in classical dynamics, difficulties. Even for spin degrees of freedom, whose Hamiltonians do not contain differentiation with respect to spatial coordinates at all, the situation does not change. The dynamic equations in this case are first-order equations,

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but they are written for a complex function and, therefore, in a certain
in a sense, are equivalent to the second-order equation of a real function.
Damping for the stochastic resonance model must be introduced here too. But
the forces leading to spin relaxation also have
the nature of thermal disturbances.

A way out might be to claim that the random external force has the same physical nature as the signal, that is, electromagnetic. But we have already seen that the signal and noise at the input must be
comparable in magnitude so that the stochastic resonance mechanism
worked in the field of signal-to-noise ratios equal to unity. The problem of biological detection of a weak electromagnetic signal
would then be reduced to the problem of detecting a weak sum of electromagnetic signal and noise, which certainly would not bring any greater clarity. The difficulty of applying the stochastic resonance mechanism to
microscopic particle is that there is no sufficient basis for writing the corresponding equations.

■ Thus, the idea of stochastic resonance in relation to a micro-particle—a potential target of the magnetic field—seems unlikely for the following reasons:

—the “gain factor” of the signal at stochastic resonance is far from reaching the value of the order of 1010 necessary to explain
MBE in the low-frequency region,

— the amplitude of magnetic signals is far from what was expected
the level of noise disturbances of the particle; stochastic resonance, however, could manifest itself only under conditions of such a correspondence,

— it is difficult to justify the entry of the corresponding dynamic equation for a microparticle.

3.5.4 Stochastic resonance in chemical reactions

Bezrukov and Vodyanoy [288] showed that stochastic resonance can
may also occur in physicochemical and other systems controlled by thermal transitions across an activation barrier. The reaction rate for such systems, proportional to the Boltzmann factor, is approximately described by the empirical Arrhenius equation

$$k \ddot{y} a \exp(\ddot{y}U/\ddot{y}T) ,$$

where a is a constant, U is the so-called activation energy. The theory of activated complex (see, for example, [62]) showed that U is, mainly,

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the height of the potential barrier separating the states of the reactants and reaction products. In some cases, the barrier height depends on an external parameter. For example, when the transition through the barrier is accompanied by displacement of the effective charge q, the barrier height depends on the electric field strength E. Then the reaction rate can be written in the form

$$k = k0 \exp(dE/\ddot{y}T) , \qquad (3.16)$$

where k0 is the reaction rate in the absence of voltage E, d is the dipole moment of transition. The rates k have the meaning of time-averaged quantities measured in the experiment. On the microscale of time, a chemical reaction is a sequence of individual random events - elementary acts of a chemical reaction. Such a sequence is described by a Poisson flow. In the case under consideration, the statistical parameter of the flow, its density, is modulated by an external field. In [288], the spectrum of the flow was studied when the external

the field was an additive mixture of noise and weak low-frequency signal:

$$E(t)= EN(t)+ ES \sin(2\ddot{y}fSt) , ES \ll EN .$$

In the absence of the control field E, the spectral density is close to a uniform density of white noise. Pulse duration of a single event ÿ determines the upper limit fc of this spectrum. In in the presence of a control field, a low-frequency band appears in the spectrum discrete component proportional to ÿ(f ÿ fS). The authors introduce signal-to-noise ratio R as the ratio of the amplitude of a discrete component components to the intensity of a continuous spectrum in a certain narrow frequency range interval f of the discriminator near fS. The signal-to-noise ratio is is called dependent on the variance of noise in the control voltage D = E2 N(t), where the angle brackets denote ensemble averaging. The calculated relative value R is equal to

$$R(D)/R(0) = \exp(\ddot{y}D/2) + fc \left[\frac{k0}{2} \left(\frac{D}{2}\right)^{\ddot{y}} \frac{1}{n!\, n^{Dn\ddot{y}1}} \right]^{-1} . \qquad (3.17)$$

Here R(0) = E2 Sk0/4f is the original signal-to-noise ratio. Graph This dependence for the ratio k0/fc = 10ÿ2 is shown in Fig. 3.8 and demonstrates a 4-fold increase in signal-to-noise ratio with increasing noise intensity from 1 to 2.

The very fact of such behavior of a non-dynamic system is interesting. We will show, however, that the application of formulas to real chemical systems is difficult. After amplification, the absolute value of R is intended to be

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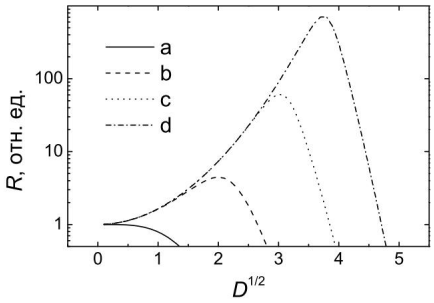


Fig. 3.8: Dependence of the signal-to-noise ratio on the noise intensity for the parameter values k0/fc = 1 — a, 10ÿ2 — b, 10ÿ5 — c, 10ÿ8 — d.

should be close to one. It is easy to find that under these conditions the ratio must be satisfied

$$E2 \; Sfc/f \; ÿ \; 100 \; ,$$

that is, by narrowing the frequency band of the discriminator, one can achieve R = 1 at the output for an arbitrarily small signal ES at the input. From a physical point of view, this result is questionable, since narrowing the frequency band inevitably leads to an increase in the time required to register the signal. But the lifetime of the working state of biological receptors is limited. From Fig. 3.8 it is also clear that the gain R can be arbitrarily large by choosing sufficiently short (fc = 1/2ÿÿ) pulses, or pulses with low

density of the sequence (k0). This result is also incompatible with reality. Apparently, the difficulties of this model are related to the excessive mathematical idealization in the description of a physical system.

Calculating the Fourier spectrum of the flux of single reaction events assumes the presence of multiple realizations for both a random Poisson process at E = 0 and a noise process in the control voltage. As a result of these abstractions, a discrete

component of the spectrum at the frequency of the input signal. Representing the output signal as the ÿ-component of the spectral density is mathematically clear, but too far from the real situation. Any real, living or technical, system is forced to detect the original signal on the basis of only a single, and moreover, limited

in time, implementation. Fourier integral for a finite-length process ÿ does not, however, contain discrete components. The peak at the signal frequency becomes broadened. This fact significantly devalues reasoning about amplification in the phenomenon of SR.

The SR itself is not a detector or discriminator. After the SR process, if we talk about a biological receiver, is necessary

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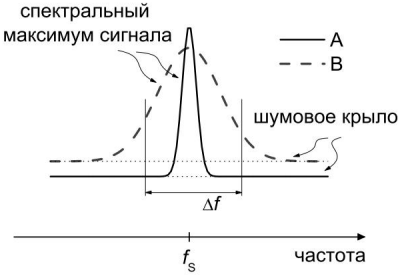


Fig. 3.9: Spectral density of signal and noise outside — A, and under SR conditions - B.

discrimination system, that is, a system that "makes a decision" about the presence of a signal in noise. From the discriminator's point of view, the signal-to-noise ratio is not the only significant parameter. Other
hym, an equally important parameter that determines the quality of the signal, is its coherence. A coherent signal in an additive mixture with noise can be detected by phase detection, accumulation phased implementations: then the signal power grows proportionally to the observation time T only ÿ T. There comes a moment when , and the noise power is proportional the signal-to-noise ratio exceeds some threshold and the discriminator “triggers”—changes its state, indicating the presence of a signal.

The signal-to-noise ratio enhancement under SR conditions is achieved by broadening of the signal's spectral line. This can be easily understood from Fig. 3.9. The signal power in the f-band, that is, the area between the signal curve and the noise wing, increases with increasing noise at SR more than the increase in the power of the noise itself. The broadening of the component signal in the spectrum of the mixture means a loss of signal coherence. Information about the signal phase is lost during the autocorrelation time ÿa, therefore the signal accumulation time decreases. The discriminator is forced to make a decision based on a smaller amount of information, Consequently, the probability of correct detection decreases and the probability of false alarm increases when there is no signal. Thus, There is reason to believe that with increasing noise under SR conditions, despite the improvement in the signal-to-noise ratio, the probability of correct signal detection decreases monotonically. This is consistent with common sense: adding noise does not increase the reliability of signal detection.
Nala.

Equation (3.16) clearly shows that the control field should be large enough to make any of the

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changes:

$$dE \ddot{y} \ddot{y}T .$$

In simple chemical reactions, in most cases, there is a transfer of an effective charge of the order of the electron charge e over a distance of several angstroms. Therefore, the transition dipole moment is of the order of d ÿ 10 D. Accordingly, the electric field, which significantly changes the barrier height should be around 108 V/m. In other words, the idea SR is unpromising in relation to simple chemical processes. It is reported that in some proteins that control ion transport through ion channels, there is a transfer of an effective charge of the order of 10e over a distance of membrane thickness of ÿ 5 nm, see section 3.4. Since If the required electric field is comparable to the field inside the biomembrane, then SR could, in principle, manifest itself, but reliable experimental evidence for this has not yet been found. However, even if SR does manifest itself, as discussed above, this is not necessarily associated with an improvement situations in terms of detecting weak signals.

We have considered the general limitations of the application of the SR idea in magnetobiology. There are about ten publications that have proposed and Various biophysical systems under SR conditions are considered. We will only point out some of them, without a detailed analysis, since the difficulties and limits of SR applicability are not resolved in these works.

The possible role of stochastic resonance in MBE was discussed in literature as applied to the conductivity of potential-dependent ionic channels Makeev [131], Kruglikov and Dertinger [513], Bezrukov and Vodyanoy [287].

Stochastic resonance applied to oscillatory Ca2+- biochemical processes near biological membranes have been studied Kaiser in [497]; a biochemical model of calcium oscillations was developed earlier in [449, 407]. A link in the system of chemical kinetics equations that may depend on the magnetic field is indicated. At the same time, the primary mechanism of the magnetic field action on the rate of this reaction is not commented on. Calculations of the dependence of experimentally observed quantities on MP parameters were also not received.

In [657] Semm and Beeson reported that the modulation of the geomagnetic field by magnitude is a sinusoidal signal of 0.5 Hz with an amplitude 2.5 ÿT triggered spike activity in nerve cells. ganglion synchronously with MP maxima. The authors suggested the involvement

5Spike is a short-term change in electrical potential that accompanies excitation. activity in nerve or muscle cells.

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biomagnetite crystals in the formation of the cellular response. In this case, the stochastic resonance mechanism is quite suitable for explaining the effect. Thermal vibrations of the crystal lead to the appearance
spikes at random moments in time, the imposition of a weak harmonic signal synchronizes the appearance of spikes.

■ The idea of stochastic resonance partially improves the situation in the field of possible explanations for the MBE, but not enough to resolve the problem. Perhaps the idea of the need to "amplify" the signal of an alternating magnetic field due to the smallness of its energy quantum compared to ÿT is fundamentally unsuitable for solving the problem of the primary mechanism.
MBE. Moreover, even if stochastic resonance is implemented in that
or another system, the following question arises. Does nature in this case really use SR for its natural purposes or
is this phenomenon here nothing more than an epiphenomenon?

3.6 Macroscopic Models

3.6.1 Orientation effects

All substances exhibit magnetic properties to varying degrees. Diamagnets and paramagnets are magnetized, that is, they acquire a magnetic moment in an external magnetic field. Ferromagnets exhibit spontaneous magnetization. In both cases, the magnetic moment ÿ of a magnetized particle, interacting with an external magnetic field H, causes a torque.

$$m = \frac{d}{dÿ(ÿÿ\ H)} \text{ or } m = ÿ \times H \quad ,$$

tending to turn the particle into a state with the lowest energy.
This is prevented by random forces of thermal disturbances of the environment. under certain conditions, when the magnetic forces acting on the rotational degree of freedom impart to it energy of the order of the average energy of thermal fluctuations per degree of freedom, ÿT /2, orientation
The distribution of similar particles in the medium ceases to be completely chaotic. A direction of preferred orientation appears, which in principle
could also lead to a biological response if the oriented
particles are somehow included in the metabolic system of the organ-
Nism.

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Orientation of diamagnetic molecules

Diamagnets exhibit minimal magnetic properties. They acquire a magnetic moment directed predominantly against the magnetic field. Diamagnets include substances that do not possess other, stronger forms of magnetism—spin paramagnetism and ferro- or ferrimagnetism. Almost all substances that make up living tissue, in particular water molecules,

Fats, proteins, and carbohydrates in the ground state are diamagnetic.

Diamagnetism stems from the quantum properties of molecules. Electron clouds surrounding the nucleus of an atom or molecule act as ring-shaped regions of increased electrical conductivity.
The increase in the flow of magnetic fields through such areas induces an electric current in them. current, which creates an oppositely directed magnetic field, weakening the external flow.

The existence of diamagnetism, a general phenomenon, often raises the question whether it could underlie at least some of the magnetobiological effects.

Let us consider a charge q with mass M in a “box” of size a. The energy moment in an external field is equal to ÿ = ÿÿ H. The simplifying assumption is that the moment induced by the external field is
parallel. Then the magnetic moment of the n-th state can be defined as ÿn = ÿÿÿn/ ÿH. The induced magnetic moment of an atom
is not quantized and can take arbitrarily small values. Only the magnetic moment of a closed system is quantized, in this case
a system consisting of an atom and a source of external magnetic field.

The thermodynamic equilibrium value of the magnetic moment is obtained by averaging with the Boltzmann distribution fn: ÿ = fnÿn. However, electrons at room temperature with a high probability
occupy the ground state. This is what we will keep in mind. In addition,
often electrons completely fill the inner atomic shells, and
valence bonds are formed by pairs of electrons with a net zero
spin. Therefore, to illustrate diamagnetism, the model
particles in the ground state (zero orbital angular momentum) with zero spin. This state does not experience Zeeman splitting
in MP.

The measure of diamagnetism is the proportionality coefficient
between the induced magnetic moment I of a unit volume of a substance, in our case I ÿ ÿ/a3, and the external field, that is, the magnetic

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susceptibility

$$ÿ = \frac{ÿI}{ÿH} \quad \frac{1}{a3}\frac{ÿ2ÿ}{ÿH2} . \qquad (3.18)$$

This value can be estimated by knowing the Hamiltonian of the system, for example (4.1), where the Zeeman energy must be neglected. The correction to the energy the ground state in the framework of perturbation theory then has the form

$$ÿ = ÿ| \quad \frac{q2}{8Mc2}(H \times r)\,2|ÿ = \frac{q2H2}{8Mc2}\,ÿ|(x2 + y2)|ÿ , \qquad (3.19)$$

where the constant MP is directed along the z-axis. In this formula, q and M are, of course, the charge and mass of the electron. For atoms with axial symmetry, ÿ|x2|ÿ = ÿ|y2|ÿ = ÿ|r2|ÿ/3. In many-electron

In a given atom, electrons occupy their states within the same the same volume. Therefore, the expression must be summed over all electrons. However, it is clear that the largest contribution comes from valence electrons. with the largest average orbital size, in our model this is the size box. Denoting the mean square of the radius of an atom in the xy plane as ÿ|r2|ÿ = r2, after substitution we obtain the Langevin formula for diamagnetic susceptibility

$$ÿ = ÿ \frac{q2}{6aM\,c2}\,(r/a)^2 .$$

The quantity in angle brackets is obviously of the order of unity. On the other hand, the size of an atom a is of the order of the Bohr radius, a ÿ 2/M q2.
From which follows the order of magnitude of the diamagnetic susceptibility

$$ÿ \; ÿ \; ÿ2/6 \; ÿ \; 10ÿ5 \quad ,$$

where ÿ = q2/c = 137ÿ1 is the fine structure constant.

Thus, the additional energy acquired by an atom or polyatomic molecule in a magnetic field is proportional to the diamagnetic susceptibility. The electron shells of molecules are not spherically symmetric. This manifests itself in the anisotropy of the diamagnetic susceptibility, that is, in its dependence on the relative orientation of the molecule and
MP. The energy correction is always positive, as follows from (3.18), equal

$$ÿ = ÿÿa3H2/2 \; ÿr2$$

and is minimal for molecules with electron shells oriented along the field. In thermodynamic equilibrium, the number of such oriented molecules is increased, which is equivalent to the appearance of an oriented

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moment of forces when turning on or changing the magnetic field. The probability density of the orientation of a diamagnetic molecule at an angle ÿ to the magnetic field is proportional to the Boltzmann factor

$$ÿ = \exp ÿ(ÿ)a3H2/2ÿT\ ÿ \exp [ÿÿ(ÿ)/ÿT\ ] \quad ,$$

which for low-atomic molecules is practically indistinguishable from unity. This means that the molecules are equally likely to be oriented in all directions.

However, the energy of a molecular structure such as a polymer assembled from identically oriented anisotropic molecules increases with the size of the polymer in proportion to the number of molecules N.
Accordingly, the degree of orientation of such rigid structures, possessing the same number of rotational forces as a single molecule,
degrees of freedom, determined by the factor

$$ÿN\ ÿ\ 1+ Nÿ/ÿT\ .$$

Therefore, for sufficiently large and rigid molecular stacks, N ÿ
105–1010, the diamagnetic orientation becomes significant.

Kuznetsov and Vanag [119] considered various variants of ordered molecular structures from identically oriented anisotropic molecules and came to the conclusion that fields exceeding 1–10 T
could cause a noticeable orientation and, consequently, a biological response. Of course, the mechanism of orientation of diamagnetic molecules and their complexes are unable to explain the biological effects of weak
MP.

In a weak magnetic field, the paramagnetic susceptibility of radicals is also small, molecules with an unpaired valence electron [252]:

$$ÿ\ ÿ\ ÿ2_{B}/a3ÿT < 10ÿ3\ ,$$

where ÿB is the Bohr magneton. Such molecules do not form ordered complexes. Therefore, their spin paramagnetism is three orders of magnitude greater strong compared to diamagnetism, also cannot be the physical basis for magnetoreception of weak magnetic fields. Dorfman [82] considered the effect of drawing diamagnetic and paramagnetic molecules into the region stronger field in inhomogeneous magnetic fields and found that the effect could have biological consequences in fields of the order of 0.1–1 T.

It is known that in a number of aromatic substances the occurrence of residual magnetization is possible, due to the fact that ÿ-electrons
molecular rings of aromatic substances form ring currents,

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capable of capturing magnetic flux similar to the Meissner effect in superconducting rings. Such substances, when specially prepared, behave like paramagnets [606], and in a crystalline state form have a weak permanent magnetic moment, of the order of 10ÿ4 ÿB per molecule [191]. Due to its small size, the realization of this effect in the mechanisms of magnetoreception is hardly probable.

Biomagnetite in a magnetic field

It is necessary to highlight a separate group of macroscopic models, or rather, one single idea, developed by many authors. Its essence lies in the presence of crystals of a ferromagnetic compound, magnetite, in a multicellular organism. Such a crystal, in a constant magnetic field, experiences a significant, many orders of magnitude greater, than in the case of diamagnets, the torque. Therefore, it can exert pressure on the corresponding nearby receptor [156, 553]. Apparently, this mechanism does indeed take place. Magnetite crystals have been found in the brains of some birds, which are known to have the ability to orient themselves in the geomagnetic field [707, 28, 270, 603]. Such crystals have also been found in some insects [459, 591] and bacteria [319, 439].

However, this mechanism of magnetoreception stands apart and does not solve the main problem of magnetobiology. After all, unicellular organisms that lack magnetite are also able to sense magnetic field. The main problem of magnetobiology is precisely in explaining this, paradoxical from the point of view of traditional physics, ziki, phenomena.

In [511] Kobayashi, Kirschvink and Nesson proposed a mechanism for explanations of the biological effects of low-frequency magnetic fields on cells *in in vitro* taking into account ferromagnetic contamination. Contaminating magnetic particles are present not only in the dust of the air, but are adsorbed on surfaces of laboratory equipment, are part of plastics and glass, into laboratory chemicals and water. The average size of such particles is about 10ÿ5 cm, they consist of ferro- and ferrimagnetic substances— that is, they possess spontaneous magnetization. The saturation magnetic induction varies approximately in the range Js = 500–5000 G.

The authors showed that common laboratory procedures of pouring and rinsing lead to enrichment of cell cultures *in vitro* magnetic particles, and their number can be tens of times greater

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increase the number of cells. The energy of a magnetic particle of volume V in a magnetic field of magnitude H = 0.5 G is equal in order of magnitude to ÿp = JsVH ÿ 10ÿ12 erg, that is, it exceeds the energy ÿT by approximately two orders of magnitude. According to the authors, such a particle, being adsorbed on the cell surface, can transfer its energy to nearby cellular structures such as mechanically activated ion channels.

The difficulty is that the energy is exceeded many times magnetic particle level ÿT in itself does not explain the effect. This energy must be somehow transferred to the molecular level. The transfer of kinetic energy is impossible due to the difference in size and masses of the particle and molecule. For a molecule with thermal velocity vm, the particle is like a wall moving at a speed vp ÿ 2ÿ/Mp. It is easy to find that as a result of the collision the velocity of the molecule cannot increase by more than 2vp. The relative increase in the energy of the molecule will be no more than 4vp/vm. Substituting the velocity estimates from the energies and masses of the magnetic particle and molecule corresponding to them, the most dem

$$\frac{\ddot{y}}{\ddot{y}} \ddot{y}\ 100 \quad \frac{\overline{Mm}}{MP} \quad 1\ .$$

Thus, if we can talk about a mechanism that utilizes the energy of the magnetic moment of a magnetic particle, then it is rather realized through the pressure exerted by the particle on the adjacent tissue, that is, through the transfer of potential energy. However, in this case energy is transferred simultaneously to a large number of molecules, so that the share of each may be small in comparison with ÿT energy. Here Detailed calculations are needed.

The mechanism is suitable for explaining the reception of constant MP. In relation to variable fields, it raises doubts. The natural frequencies of oscillations of a magnetic particle embedded in elastic tissue are significantly higher than the low-frequency range. Therefore, it is difficult to explain the low-frequency, and especially the amplitude, efficiency windows on this basis. new is hardly possible.

Edmonds [385] discusses the possibility of recycling magnetic properties of a suspension of liquid crystal nematic and microcrystals magnetite in the magnetic compass orientation of birds. In an idealized model situation, a suspension of nematic with filiform microcrystals of magnetite was placed between glass plates with specially treated surface, which provided a certain anisotropy of the director vector of the liquid crystal. In this case, the polarization of the radiation passing through the stack changed in

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depending on the applied magnetic field. The torque acting
onto microcrystals, was transferred to nematic molecules and changed the direction of the director. The relative intensity of the radiation was measured,
passed through two crossed polarizers, between which a system with a liquid crystal substance was placed. The dependence of the intensity on the magnetic field had the form of a curve with saturation, and the maximum
the slope was about 3%/ÿT. The orientation of the magnetic moment of a droplet with a diameter of 5 ÿm containing microcrystals is estimated
magnetite in a liquid matrix at a concentration of 10ÿ3 by volume. Orientation is quite significant even in a field of 0.15 ÿT, which could be the basis for the mechanism of the optomagnetic orientation ability of animals.

From the point of view of the effectiveness of such a mechanism, the possible presence in the eyes of birds of structures containing elongated molecules of dyes such as ÿ-carotene, which absorb light radiation, was discussed.
at a certain orientation to the electric field vector, and magnetite microcrystals that provide orientation of the dye molecules
in MP.

This mechanism is based on the interaction of magnetic microcrystals with nematic molecules. Liquid crystal molecules and
themselves have general magnetic properties of the diamagnetism type. The anisotropy of the induced magnetic moment leads to
rotation of the director in the magnetic field. However, this effect is too small to explain the MBE. Only optomagnetic sensors of strong magnetic fields are known,
of the order of tens of Teslas built on this principle.

3.6.2 Eddy currents

One of the mechanisms of the IBE establishes that the acting factor
when irradiating biological systems with low-frequency magnetic fields are
eddy electric currents induced by alternating magnetic fields in biological
gic tissues.

The magnitude of the current is generally proportional to the strength of the electric field E associated with the magnetic field B according to one of the equations of Max-
Vella

$$\mathrm{rot}E = -\frac{1}{c}\frac{\ddot{y}B}{\dot{y}t}.$$

For a sinusoidal magnetic field with frequency ÿ and amplitude b, the amplitude
electric field is proportional to the product ÿb. If the hypothesis
is true, then the MBE in the experiment should have correlated with changes in this value. However, in the case of relatively weak correlations,
of the order of GMF, no fields were detected.

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In [496] Jutiläinen reports the absence of dependence of the MBE on ÿB/ÿt. In [527] Liebow, Smith, and MacLeod pointed out four independent works with different biological systems in different ranges of alternating magnetic fields, where the eddy current hypothesis was tested and not confirmed. In particular, Libow, Williams et al. [697] investigated the effect of alternating magnetic fields on the increase in the rate of DNA synthesis in human fibroblasts in the range b(1.6–400)f(15–4000), however, the effect is, on average, no more than 50%, did not depend on the product bf, which varied within the range four orders of magnitude.

The statistically significant ÿ 6% change in the rate of fibroblast cell proliferation measured by Ross in [642] is practically did not change under various magnetic conditions corresponding to the cyclotron configuration of calcium ions: B(131)b(131)f(100), as well as B(98)b(98)f(75) and B(21)b(21)f(16). As can be seen, the product fb changed almost 40 times while maintaining the magnitude of the effect.

In [316] Blackman, Benan and House showed that a 50 Hz MF with an amplitude in the range of 0–42 ÿT against the background of a constant field of the order of geomagnetic, it dampens the action of a substance that induces neurite growth in some animal cells by approximately two times. Such changes arose starting from amplitudes of 6 ÿT and stabilized at a new level by 10 ÿT. Therefore, to clarify the role of induced electric The field amplitude was chosen to be 8 ÿT, corresponding to the maximum sensitivity of the system to changes in magnetic field. Petri dishes with concentric compartments of different diameters containing cells were placed in a uniform magnetic field. coaxially with the vertical solenoid. In this configuration, the electrical the fields in different compartments differed significantly and varied in am- the plate from 3 to 65 ÿV/m, and the magnetic field was the same. Measurements showed the same level of quenching in different compartments, which indicated on the insignificance of induced electric fields.

The results of recent work by Genrow, Smith and Liebow [491] also showed the absence of correlation between the MBE and induction currents.

Convincing evidence against the eddy current hypothesis was presented by Prato, Cavaliers et al. in [530], where the parameters BDC,BAC and f simultaneously increased by 2 and then 4 times. In this case, the product fBAC increased up to 16 times, but the statistically significant level The MBE remained constant, Fig. 4.41.

Note that with increasing amplitude or frequency of the alternating magnetic field, all there comes a moment when the induced fields and currents acquire biologically significant level, unless a small-sized biological system is placed at the geometric center of the system of ex-

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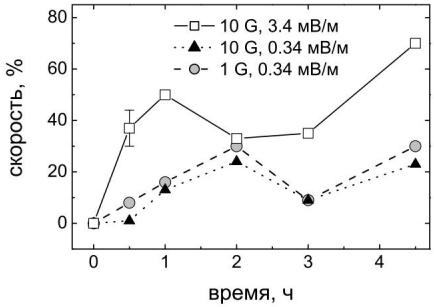


Fig. 3.10: Transcription kinetics of HL-60 leukemia cells in various electric and magnetic fields with a frequency of 60 Hz, data [368].

positions (see section 1.4.1). Experimental evidence that with the increase in the intensity of the alternating magnetic field, a correlation appears between the biological response and the product fBAC, as found in the work of Schimmelpfeng and Dertinger [652]. Green, Skavronsky, and others in [368] conducted A special study of the transcription rate of human leukemia cells HL-60 in Petri dishes with concentrically divided compartments placed on the axis of a solenoid with an alternating magnetic field of 60 Hz was carried out. The kinetics of the incorporation of the radioactive label 3H, introduced into the cell culture with uridine, into the synthesized RNA molecules is shown in Fig. 3.10.
The cells were located at a distance of about 0.2 and 2 cm from the axis and tested, In addition to the magnetic field, the effect of the induced electric field. As can be seen, the cells responded specifically to changes in the electric field, not the magnetic field. thread field.

Eddy currents can induce a biological response either by heating the tissue through Joule heating (Section 1.4.1) or by electrochemical effects due to the action of induced electric fields on charge carriers in the tissue, ions, charged molecular groups in various biophysical structures.

[608] Polk considered a possible mechanism of the effect of low-frequency magnetic fields on the distribution and dynamics of ions on the surface of cells. membranes. They applied the classical dynamics of charges in magnetic fields in the presence of thermal diffusion and phenomenological attenuation. The equations of electrodynamics of continuous media for current density were used.

$$\vec{j} = \rho \quad \frac{\partial \rho}{\partial t}, \quad \vec{j} = u\rho\vec{E} \quad \frac{u}{q}\rho T\nabla\rho.$$

The first equation, the continuity equation, relates the current density with a density ρ of free charges q with mobility u. The second equation shows that the current is determined by the electric field E and the dif-

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fusional thermal resorption of distribution inhomogeneities
charge density. From here, one can find the magnitude of the disturbances in the distribution due to the action of vortex electric fields.

It was shown that the induced currents on the membrane surface would exceed the thermal level under certain conditions.
In particular, the movement of ions should be limited to a thin, order of magnitude $10\ \text{Å}$, layer on the cell surface, and the cells themselves must form macroscopic, > 3 cm, closed chains. The threshold was found
the product level fB ÿ 1 T/s for exposure in sinusoidal
MP. This, for example, corresponds to an amplitude B ÿ 100 ÿT at a frequency f = 1 kHz. Although this estimate is based on a possible electrochemical mechanism, it is close in order of magnitude to the threshold of thermal effects (see Section 1.4.1). Note that the condition of macroscopic cellular chains significantly limits the applicability of this model.
For example, it cannot be used to explain MBE in cellular
cultures in homogeneous solutions *in vitro.*

There are also other electrochemical mechanisms of biological effects of MP. Chiabrera et al. in [344] discussed the possibility of action induced electric fields on the transport of ions and molecules across biological membranes. A further development of this theme is the range of models described in Section 3.4.

■ Electrochemical mechanisms, in particular those based on the induction of eddy currents by an alternating magnetic field, explain only
some of the observed phenomena. They are unsuitable for explaining effects with pronounced spectral frequency-amplitude features and effects caused by weak magnetic fields.

3.6.3 Superconductivity at the cellular level

The idea of a superconducting state of biological matter is attractive because it allows us to reduce the problem of electromagnetobiology to
the problem of substantiating superconductivity in biological tissue. Indeed, if such a superconducting state exists, then the change in its characteristics under the influence of even ultra-weak magnetic fields is beyond doubt. It is precisely on the properties of the superconducting state and its interphase boundaries, the Josephson junctions [493],

see Appendix 6.8, ultra-sensitive MP meters are based,
— quantum interferometers.6 The problem of quantum theory also does not need to be explained, since we are talking about superconductivity under normal physiological conditions.

6SQUID — superconducting quantum interference device

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temperature, that is, high-temperature superconductivity. There is quite a lot of speculation on this topic in the literature.
[355, 620, 233, 574, 356].

Fröhlich was one of the first to point out the biological cell as possible receptor of EM waves [441, 442]. This followed from the mechanism he proposed for Bose condensation of certain modes of collective excitations of systems of interacting molecular dipoles in living cell, in the millimeter-wave range. Since then, attempts have continued to find other mechanisms at the cellular level that could explain the biological reception of weak magnetic fields, including those in the low-frequency range. For example, in [356] the possible presence of superconductivity in living cells and the manifestation of Josephson effects at contacts are discussed. between superconducting regions. It is argued that properties analogous to the dynamics of Josephson junctions are observed in single cytoskeletal cells and for two adjacent cells. Consequently, EMFs can influence intercellular communication.

Electronic bisolitons, carrying a double elementary charge and propagating along alpha-helical protein molecules without attenuation, were considered theoretically by Davydov in [366]. The method experimental evidence for the existence of bisolitons in living organisms has not been offered.

A kind of manifesto of superconductivity on the cellular level level is Miller's review [574] which contains a voluminous bibliography of works in this area. At the same time, there are sufficient theoretical basis for the emergence of the superconducting phase in There are no cellular structures today. There are also no constructive predictive models of this phenomenon. It should be noted that high-temperature (300 K) superconductivity as a physical effect is still has not been detected. Therefore, the idea of the emergence of a high-temperature superconducting state in biological tissues is doubts.

There have been attempts to substantiate this idea experimentally. They are based on the fact that indicators of a superconducting state are the anomalously high conductivity of the medium and, accordingly, anomalous diamagnetism, as well as the quantization of the magnetic flux through the surface bounded by the superconducting circuit. The latter leads to the current in the circuit, with other parameters fixed,

takes only a discrete series of values. For some, quite under harsh conditions, in particular, in the presence of a section with impaired superconductivity in the circuit, a Josephson junction, it is possible

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observe current oscillations and electromagnetic radiation of characteristic
frequency with increasing emf included in the circuit. In [574] a number of experimental
works are indicated that interpret the data of magnetic measurements of biological and
organic media as the presence of molecular or subcellular domains of superconductivity.

We note the experiments of Ahmed, Calderwood, and others [427], in which
measured the diamagnetic susceptibility of weak solutions of the enzyme
lysozyme in a static magnetic field of 40–200 mT. The dependence of susceptibility on
magnetic field, temperature, and enzyme concentration had a complex polyextreme
character. The maximum susceptibility was observed in
in the region of 60 mT, with the susceptibility per molecule
exceeded normal values by more than a thousand times. To explain
The authors proposed superconducting domains with disruption of superconductivity in a
stronger magnetic field.

Del-Giudice, Doglia et al. believed that the biological membrane separating the two has
the properties of Josephson junctions.
new cells during mitosis of the original cell, [552]. In this work
The authors suggested that phenomena similar to the Josephson effects
can occur not only at the contacts between superconductors, but also
in a more general case, at the boundaries between the phases of a correlated state. The
role of electron pairs in this case should be performed
quasiparticles – carriers of correlation, for example, coherent bosons
excitations of molecular dipoles in the Fröhlich model (see Appendix 6.7). Leaving aside
these highly abstract ideas, let us consider
experiments described in [552]. They, as the authors believe, substantiate the existence of
superconductivity or similar macroquantum
states in biological tissue.

They measured the current in a circuit, the element of which was a cell with a cellular
culture *of Saccharomyces cerevisiae* in deionized sucrose solution in the state immediately
before, during and after mitosis.
The cells in the cell between the electrode needles formed chains similar to pearl strings,
which were recorded using a microscope.
The cell voltage was also measured using a current generator.
With an internal resistance of 12 megohms, the current in the circuit was slowly increased
and voltage surges across the cell were observed. That is, the volt-ampere dependence
was stepwise. This effect is not
arose in a culture of cells incapable of division. In general, such
dependence is characteristic of the current in a superconducting circuit with a Josephson
contact, since the magnetic flux through the circuit takes only a series of values that are
multiples of the magnetic flux quantum.

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they disappear when the superconducting component of the current reaches a critical value and destroys specific quantum phenomena in the region
contact.

What was significant for the observation was that the synchronized cell suspension showed current and voltage surges only during cytokinesis, the final stage of mitosis, when the formation of
partitions between daughter cells. In addition, voltage surges had a magnitude in the range of 0.3–3 of the average value, which is more likely
is associated with the range of cell sizes. Considering the fact of such a wide range of jump sizes and the fact that dividing cells formed threads between the electrodes, another explanation is plausible.
observations that do not appeal to the idea of biological superconductivity. At the moment of formation of two cells from one, the electrical resistance increases abruptly, which leads to abrupt growth
voltage on the electrodes and some drop in current in the circuit. Fact
a small drop in current in the circuit is clearly visible on the operating graphs
[552] and indicates that the internal resistance of the current generator is comparable to the resistance of the cell. It is remarkable that the level
The external magnetic field influenced the magnitude of voltage surges. The average values of the V surges were 1580, 470, and 15 nV at H field levels of 400 mT, 50 ÿT, and ÿ1 ÿT, respectively. The latter value
1 ÿT was not measured, but it is typical for magnetic fields inside magnetic screens made of mu-metals, where the corresponding measurements were carried out. This
the series forms a dependence V(H) close to logarithmic, which is surprising in itself. However, in the framework of superconductivity phenomena
This behavior doesn't fit.

In this work, electromagnetic radiation from cells at the cytokinesis stage was also observed. Radiation was also observed by other authors, Hoelzel and Lamprecht in [474] and Berg in [282], under similar conditions. Radiation
yeast cells in the range of about 7 MHz had a spectral maximum with a width of ~5 kHz. Measurements were carried out in a magnetically shielded chamber, when the above-described experiment with voltage surges yielded a value of about 15 nV. As the authors suggested, the radiation accompanies quantum transitions of the system to the next current state. The following coincidence served as the justification. The calculated

frequency of radiation from a Josephson junction fed by a source
voltage of 15 nV is equal to eV/ÿ ÿ 7.3 MHz, which falls within the range of values observed in the experiment. But with such a justification it is difficult
agree. Even if we admit for a while that in both cases, - with
voltage steps and with radiation, the Joe effect takes place.

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Zefson, there is a significant contradiction. In the first case, it would be stationary effect, and in the second - a non-stationary Josephson effect. The magnitudes of the stresses in these modes have different physical meaning. Therefore, it is impossible to use the voltages obtained in one mode to calculate the effects of the second mode.

Note that radiation from dividing cells could occur due to current pulses on the surface of membranes due to the redistribution of surface charges at the moment of formation of two cell membranes from one. The duration of the pulses can be easily estimated from formulas for the mean square of the diffusion displacement of ions r2ÿ 6Dt, where D is the diffusion coefficient, see p. 347. Substituting the characteristic size of the charge redistribution region of 0.1–1 μm and taking into account that the diffusion of ions on the cell surface, the so-called lateral diffusion, is one to two orders of magnitude faster than diffusion in the volume [85], we find the order of magnitude of the pulse duration is 0.01–1 ÿs. Such pulses create an electromagnetic field in the range of 1–100 MHz. This The range reflects the uncertainty of the estimate, not the width of the radiation spectrum. The width of the spectrum is ultimately determined by the spread of physical cell parameters, primarily the range of their sizes.

■ The experiment under discussion and the Josephson effects are more likely just an external similarity, and not a kinship of causes. Biological Superconductivity remains today one of the bold hypotheses in magnetobiology, interesting, but lacking a reliable theoretical basis. and experimental justification.

3.6.4 Magnetohydrodynamics

Magnetohydrodynamic effects are considered during the flow of blood through vessels or other bioplasma in a magnetic field, see review [119]. For example, they investigate the additional pressure on the walls of blood vessels due to the action of the Lorentz force on free charges in the blood. In this case, they usually overlook the fact that the macroscopic effects of pressure are provided by corresponding processes at the microscopic level. If it is not possible to explain a significant change in state of one individual microparticle in a magnetic field under similar conditions, then any positive statements regarding macroscopic consequences look unconvincing. Such statements must contain errors of inference - mathematical, physical and, most often, logical and conceptual, that is, associated with the use of regularities outside the area of applicability.

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Magnetohydrodynamics studies the interaction of electromagnetic fields and moving liquid or gaseous media with relatively
high conductivity, like metallic. The movement of the medium in the magnetic field induces currents in the medium. The latter, on the one hand, are subject to the action of an external magnetic field, and on the other hand, are themselves a source of additional magnetic fields. To assess the degree of influence of a magnetic field on the flow of a liquid, the Hartmann number, the ratio of the density of magnetic and viscous forces, is used [123]

$$G = \frac{rH}{c}\sqrt{\frac{\sigma}{\eta}},$$

where r is the characteristic length, ÿ is the electrical conductivity of the medium, ÿ — viscosity coefficient. Hartmann investigated the flow of a viscous incompressible fluid between two planes in a direction perpendicular to them
MP H showed that if G ÿ 1, then magnetic effects are small. Conversely, if G ÿ 1, then the viscous properties of the liquid can be neglected.
For example, the movement of blood with a conductivity of ÿ 1 S/m = 9·109 CGS units and a viscosity of 0.01 g/cm s in a vessel with a diameter of about 10ÿ2 cm in MP ÿ 1 Gs is characterized by the Hartmann number G ÿ 10ÿ6. Consequently, there is no basis for studying magnetohydrodynamic effects in magnetobiology.

To estimate the magnitude of other possible effects, we move to a reference frame moving together with the liquid in a magnetic field H with
velocity v. In such a system, an electric field arises, equal in magnitude to order of magnitude E ÿ vH/c. Generally speaking, the EP could orient molecules that have a dipole moment, for example, water molecules with a moment d = 1.855 D. However, the additional energy dE,
acquired by a water molecule in the specified EP, with an MP value of 1 Gs and a velocity of 1 cm/s, fourteen orders of magnitude smaller than the disordering thermal scale ÿT . This completely invalidates the discussion of biological effects due to dipole orientation. Another
the scenario takes into account the separation of ions of opposite signs opposite sides of the movement area. Work on moving
charge e at a macroscopic distance r in a field E is equal to erE, while while the diffusion processes that impede such movement have the same energy scale ÿT . It follows from this that
that in this case there are still five to six orders of magnitude missing for observation changes in the concentration of ions on the walls of the volume, even with dimensions r ÿ 1–10 cm.

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3.6.5 Macroscopic charged objects

Macroscopic objects, targets for weak magnetic fields, are selected based on their sufficiently large intrinsic energy, comparable to ÿT. Then the problem is resolved, as it were, by itself. Indeed, even a weak magnetic field is capable of significantly altering the energy.
an object carrying, for example, a large electric charge [101], or
possessing a high speed of relative motion. True for
This requires strictly defined conditions of the object's motion. The change in the object's energy in the magnetic field is mentally associated with some biochemical processes. However, in *all* known to the author
In works of this class, the existence of such objects was *postulated.* They were not observed as such in any other experiments not related to magnetobiology. Therefore, the postulation
The value of these objects seems poorly justified. Valuable can be recognized a model in which minor assumptions or even idealization
leads to significant consequences. Here, however, the "weight" of the postulate is comparable to the "weight" of the problem itself. To postulate the existence similar objects - macroscopic charged ion vortices
[101] etc., is the same as postulating the absence of the problem of magnetobiology as such.

Karnaukhov and Novikov [102] explained the MBE and the effects of combined magnetic resonance with cyclotron frequency on amino acid solutions. They instead of individual ions in solution in MP, their clusters were considered macroscopically large number N of ions. The average value of random forces acting on the cluster from the environment surrounding it,
at sufficiently large N becomes less than the average value of the force from the magnetic field, that is, the Lorentz force. This, according to the authors' intention,
The problem seems to be resolved. Let's note the following difficulties with this idea.

Firstly, the nature of the interionic forces that ensure the existence of the cluster is unclear. Clustering is known in systems with thermal
the movement of particles polarized under the influence of EMF, i.e. particles with a dipole moment (see review by Ivanitsky, Medvinsky et al. [152]).
But here the authors are considering particles - ions. Secondly, according to [102], a cluster is a system with mass NM and charge Nq, the dynamics of which in the MF is determined by the motion of the center of mass, otherwise the concept cyclotron frequency for the cluster would lose its meaning. Then the thermal
the energy of motion of the center of mass is the same as that of an individual ion, since
both the ion and the cluster in this sense are identical to a point particle
with three degrees of freedom. Thermal energy, as is known, is distributed uniformly between the degrees of freedom, and not between individual ones.

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parts of the system.

At the same time, the contribution to the cluster energy from the MF does not increase with the growth of its charge in proportion to N, as it might seem due to the increase in the Lorentz force. The author's work [26] provides an estimate of the instantaneous power of the process of converting the energy of an alternating magnetic field into the energy of the angular momentum of a classical particle, formula (20) of the original article. In the notation adopted here, the formula has the form7

$$G \ddot{y} \ddot{y}1\ddot{y}L,$$

where ÿ1 = qHAC/2Mc is the Larmor frequency associated with the amplitude alternating magnetic field, L is the angular momentum. Note that the Larmor frequency, like the cyclotron frequency, is equal for an individual ion and for an ion cluster. Therefore, it is interesting to estimate the angular momenta L of the ion and the cluster. In fact, the question is: are there any mechanisms or structures in living tissue or solution that are capable of
ensure a non-zero angular momentum of a particle over a time of the order of ÿÿ1? For an ion, it can be assumed that such a structure is the cavities of macromolecules. Once in a cavity, the ion
time preserves the initial angular momentum and, therefore, is able to exchange energy with the MP. For a cluster, as a macroscopic system,
It's difficult to suggest anything. The only reasonable assessment is
In this case, L = 0, since there are no reasons that could force
the center of mass of a cluster experiencing multiple thermalizing
collisions, to move in a circle or arc. There are no reasons and
for the existence of angular momentum of a toroidal cluster; the postulation of such a cluster shape is also found in the literature.
Thus, it is difficult to agree that ion clusters are in any way
clarify the problem of magnetobiology.

Generally speaking, ions in solution acquire angular momentum in the magnetic field, but this effect is extremely small. It can be easily estimated from the equation

$$\frac{dL}{dt} = K = r \times \frac{q}{c} v \times H \quad ,$$

where L is the angular momentum, K is the rotational momentum, and r is the radius vector of the particle. Obviously, the derivative dL/dt is bounded from above by the value rqvH/c. Since the ion experiences thermalizing collisions

7For a quantum particle, the energy splitting in the magnetic field is ÿm ÿ mÿ0 = mqH/2Mc. In an alternating magnetic field dH ÿ Hÿdt, from which the power estimate follows dÿm/dt ÿ ÿ1ÿm. Here m is the angular momentum of the m-state.

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with particles of the medium, the estimate of the angular momentum in the interval between collisions is

$$L \ddot{y} \ddot{y} rqvH/c \ddot{y} \ddot{y} 2qv2H/c ,$$

where r ÿ 10ÿ8 cm is the length and ÿ is the mean free time. Since the square of the velocity of a particle in a solution is equal in order of magnitude to ÿT /M, then for ÿ ÿ 10ÿ10 s, ÿc ÿ 100 Hz

$$L \ddot{y} \ddot{y} T \ddot{y} c\ddot{y}^{2} .$$

That is, the angular momentum of a free ion is much less than the quantum uncertainty of the moment. Let's find the diamagnetic one to be convincing contribution associated with the occurrence of such a moment. The gyromagnetic ratio for orbital motion is ÿ = q/2Mc, then the magnetic the moment of unit volume is I = ÿL/r3, and the diamagnetic susceptibility ÿ = ÿI/ÿH

$$\ddot{y} \ddot{y} \frac{q}{MckT} \frac{\ddot{y}\ddot{y}c}{\ddot{y}H} \frac{\ddot{y}^{2}}{r3}{}^{\ddot{y}} \frac{q2}{Mc2r} \ddot{y} 10\ddot{y}9 .$$

There is no need to average over an ensemble of particles, since This value is immeasurably small. It is several orders of magnitude smaller than atomic electron diamagnetic susceptibility, see section 3.6.1.

3.7 Cyclotron resonance in magnetobio-

logy

In a number of cases, the biological effects of weak MFs have a resonant character, and the effective frequencies, as initially established in [524, 527], are close to the cyclotron frequencies of Ca2+, Na+ ions. and others. This allowed us to assume that the cyclotron resonance lies at the basis of the observed phenomena. The emergence of the idea of cyclotron resonance in magnetobiology is associated with the name of Libow from the Auckland University, USA. The topic of such resonance in magnetobiology was developed by various authors, but was not recognized due to the impossibility of a correct physical justification. At the same time, these experiments demonstrated the significant role of ions, especially Ca2+

in magnetobiology. About 12% of papers on electromagnetobiology contain discussions of the role of ions and 9% of the role of calcium.

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3.7.1 The concept of cyclotron resonance

The equation of motion of a classical charged particle in electromag-
thread field

$$E = \ddot{y}\text{gradA0}\,\ddot{y} \qquad \frac{1}{c}\frac{\ddot{y}A}{\ddot{y}t}, \quad H = \text{rot}A \tag{3.20}$$

has the following form (see, for example, [121]),

$$M = \frac{dv}{qE} + dt \qquad \frac{g}{c}v \times H \quad , \tag{3.21}$$

where the right-hand side is called the Lorentz force. Considering that the kinetic energy of a particle is ÿ = Mv2/2, it is easy to find from (3.21) the rate of change of energy dÿ/dt, [121]

$$\frac{d}{}\ddot{y} = qvE \,.\, dt \tag{3.22}$$

Let the particle move in a plane perpendicular to the direction
H z, and the E field is directed along the x axis. Let the electric field
(EP) Ex ÿ cos ÿt is so small that the orbit of the particle is small
changes over time ÿ ÿÿ1, so the particle can be considered free.
According to (3.21), its motion in the magnetic field occurs in a circle with a cyclotron
frequency ÿc = qH/M c. Then the x-component of its velocity, c
accurate to phase, changes as cos ÿct. Accordingly, from (3.22)
we walk

$$\frac{d}{}\ddot{y}\ \ddot{y}\ \cos\ddot{y}t\cos\ddot{y}ct = dt \qquad \frac{1}{2}\cos(\ddot{y}\ \ddot{y}\ \ddot{y}c)t + \qquad \frac{1}{2}\cos(\ddot{y} + \ddot{y}c)t.$$

The change in energy is determined mainly by the first term with
low frequency ÿ = ÿ ÿ ÿc. Let this change be measured over an interval
time from t ÿ T to t + T . Relative to the value of the interval, it is equal to

$$\ddot{y}T = \frac{1}{2T}\int_{t\ddot{y}T}^{t+T} \cos\ddot{y}\ddot{y}\, d\ddot{y} \ddot{y} \cos\ddot{y}t \,.\, \frac{\sin\ddot{y}T}{\ddot{y}T} \tag{3.23}$$

The change in energy can be either positive or negative, depending on the random moment of observation t. Therefore, the intensity of the process of change in the energy of a particle is conveniently characterized by the mathematical expectation of the square of the quantity (3.23), that is,

$$I = \ddot{y}2\overline{\ }_{T}{}^{\ddot{y}} \qquad \frac{\sin\ddot{y}T}{\ddot{y}T}^{2} \quad ,$$

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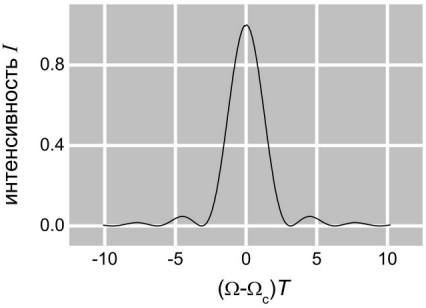


Fig. 3.11: The intensity of energy exchange between EM measured over the time interval [ÿT,T] field and a charged particle at cyclotron resonance.

where the bar denotes the averaging of the ergodic process over the interval time T The ·

graph of this function is shown in Fig. 3.11. It shows that the greatest intensity of changes in the energy of a particle occurs in under *cyclotron resonance* conditions when the frequencies ÿ and ÿc coincide. The statement that ion cyclotron resonance also occurs at odd harmonics of the cyclotron frequency and does not occur at even harmonics [667], is not entirely justified. For example, in metals there are conditions when the time interval between successive collisions of electrons with scattering centers is, on average, greater than the period of the magnetic field. When the magnetic field vector is strictly parallel to the surface of the metal, the electrons spend only a small part of the period of motion near metal surfaces where an external electric alternating field acts on them. Then, obviously, conditions for resonance arise on all multiple frequencies. Approximately such conditions are realized and in *cyclotrons* - devices for accelerating charged particles. in the biological environment, in biophysical structures, there are no conditions for the external EP to act on ions only for a small part their orbits, if only because there are no orbits themselves. Therefore, resonances on multiple frequencies are impossible. In the case of circular EPs induced by an alternating magnetic field, resonance is possible, generally speaking, at the cyclotron frequency and its subharmonics. But this is no longer a cyclotron, but parametric resonance. This will be discussed in another section.

The idea of cyclotron resonance has been repeatedly used to explain the biological effects of low-frequency magnetic fields. Due to its clarity, it has received support from many researchers, primarily biologists. The main argument of the idea's proponents is that the magnetobiological effect (MBE)

appears predominantly at frequencies predicted by the formula cyclotron resonance ÿc = qH/M c for particles with magnitude q/M

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biologically significant ions, Ca, Mg, etc. Indeed, it was observed
the effective frequency shift proportional to H [527], and also the shift
in accordance with the mass of the ion isotope [332].

The main argument of the opponents of the idea (see, for example, the works [649, 235]) is as follows. Ions are present in a living environment in an aqueous solution at a temperature of about 300 K. Under these conditions, they have thermal energy of the order of ÿT. The motion of a particle in an MF occurs in a circle, the radius of which can be easily estimated from the equality of the thermal
energy and energy of motion:

$$R = \frac{1}{ÿc}\sqrt{\frac{kT}{M}}.$$

In a magnetic field of the order of the Earth's field, for a calcium ion this value is more than a meter. It is clear that it is incompatible with the concept of cyclotron resonance of an ion, for example, in a biological cell, the size of which is six
orders of magnitude less.

In addition, the ion in the solution is hydrated, that is, it carries
shell of water molecules. Its effective charge under these conditions is
several times smaller. Accordingly, it makes no sense to compare the frequency of the external field with the cyclotron frequency of an ion without a shell.

There are other considerations that lead to the same conclusion. An ionic particle in the cytoplasm or intercellular environment experiences
numerous thermalizing collisions with the surrounding molecules; the particle's motion is of a diffusive nature. Naturally,
that the motion, phase-matched with the external magnetic field, is limited in order of magnitude by the interval of free time, that is, the time between two successive collisions with molecules of the medium.
The order of this interval T in an aqueous solution is about 10ÿ11 s. In [649] this the estimate for calcium follows from the formula

$$T = \frac{1}{nÿv},$$

where $v = \sqrt{2ÿ/M}$ is the thermal velocity of the ion, n ÿ 4 · 1028 mÿ3 is the density of atoms in the biological environment, ÿ ÿ ÿa2 $_0$ =8 · 10ÿ21 m2 — area collision cross-sections, a0 is the Bohr radius.

It is clear that the "resonance width" ÿ 1/T (see below) is many orders of magnitude greater than the cyclotron resonance frequency. This also indicates the meaninglessness of the concept of cyclotron resonance under ion conditions in
solution.

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3.7.2 Cyclotron resonance in an ion channel

To circumvent the difficulties, they proposed cyclotron resonance of ions inside the ion channels of biological membranes, where the radius of the orbits could not be large. Ion channels are formed by coiled proteins that span membranes. They provide the necessary
for life, the exchange of ions and some molecules between
cytoplasm and extracellular environment. Most fully corresponding
The model is presented in the work of MacLeod, Libau and Smith [563]. The main idea of this work is to postulate the absence of random thermalizing collisions during the motion of an ion inside the channel. Therefore, the motion is phased with the external magnetic field for a sufficiently long time and,
thus, can be described by the equation of classical dynamics of a particle under the action of the Lorentz force.

In this article it is assumed that 1) the ion starts moving from the mouth of the channel with zero velocity, 2) the channel of cylindrical symmetry has
two constrictions - in the middle and at the end of the channel. Starting from the mouth of the channel, the ion moves in a spiral under the influence of the transmembrane potential difference and the alternating magnetic field. The main idea of the model is the ability of the ion, under specific conditions, to acquire extremely small energy near the constrictions. Therefore, the size
The diameter of the cyclotron orbits is smaller than the diameter of the constrictions, and the ion penetrates through the narrow spots of the channel. The structure of the protein that forms the channel
In this model, it acts as a filter or gate for various helical ion trajectories. The efficiency of the filter depends on the parameters
external low-frequency magnetic field. This allows us to relate the results of calculations of ion trajectories in the channel to various conditions in magnetobiological experiments.

It is known that the equation of motion of a charged particle in a medium with dissipation of energy under the influence of an electromagnetic field and external the force has the following vector form8

$$\frac{dU}{dt} = \frac{q}{m}E + \frac{q}{U \times B\ddot{y}m} \quad \frac{1}{\ddot{y}}U + \frac{1}{m}F. \tag{3.24}$$

The cylindrical coordinates Pr,Pÿ,Pz of an arbitrary vector P are equal to [512]

$$Pr = Px\cos\ddot{y} + Py\sin\ddot{y},\ P\ddot{y} = \ddot{y}Px\sin\ddot{y} + Py\cos\ddot{y},\ Pz = Pz\ .$$

8ISC system of units.

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Using these rules, after simple calculations, we find the physical coordinates of the velocity vector U

$$Ur = \frac{dr}{dt}, U\ddot{y} = r\frac{d\ddot{y}}{dt}, Uz = Uz\,dt \tag{3.25}$$

and acceleration vectors $\frac{d}{dt}U$

$$\begin{aligned}
\frac{d}{dtU}_{r} &= \frac{d2r}{dt2} - \ddot{y}\,r\left(\frac{d\ddot{y}}{dt}\right)^2 = \frac{dUr}{dt} - \ddot{y}\,U\ddot{y}\frac{d\ddot{y}}{dt}, \\
\frac{d}{dtU}_{\ddot{y}} &= r\frac{d2\ddot{y}}{dt2} + 2\frac{dr}{dt}\frac{d\ddot{y}}{dt} = \frac{dU\ddot{y}}{dt} + \frac{1}{r}UrU\ddot{y}, \\
\frac{d}{dtU}_{z} &= \frac{dUz}{dt}
\end{aligned} \tag{3.26}$$

in a cylindrical system. Substituting formulas (3.25) and (3.26) into (3.24) leads to the following equations of motion

$$\begin{aligned}
\frac{dUr}{dt} - \ddot{y}\,U\ddot{y}\frac{d\ddot{y}}{dt} &= \frac{q}{m}Er + \frac{q}{m}U\ddot{y}Bz\,\ddot{y} + \frac{Ur}{\ddot{y}} - \frac{Fr}{m}, \\
\frac{dU\ddot{y}}{dt} + \frac{1}{r}UrU\ddot{y} &= dUz - \frac{q}{m}E\ddot{y}\,\ddot{y} - \frac{q}{m}UrBz\,\ddot{y} - \frac{U\ddot{y}}{\ddot{y}} + \frac{F\ddot{y}}{m}, \\
\frac{dUz}{dt} &= \frac{q}{m}Ez\,\ddot{y} + \frac{Uz}{\ddot{y}} - \frac{Fz}{m}.
\end{aligned} \tag{3.27}$$

where, as in [563], it was assumed that the magnetic field is directed along z-axis, coinciding with the channel axis, that is, Bx = By =0.

The equations used by the authors [563] differ from (3.27) and contain inaccuracies. Further, the dissipation term ÿU/ÿ in the equation motion (3.24) implies numerous chaotic collisions of the described macroscopic particle with a multitude of microparticles, molecules of the liquid medium. At the same time, the ion in the channel experiences
The constraints are limited only by the walls, and each collision will significantly change its momentum. That is, the physical conditions under which it is permissible to use the phenomenological dissipation term are not taken into account.

The most fundamental difficulty of the model is related to the rigid initial conditions for the ion. It is necessary to have close to zero initial velocity of the ion, so that the cyclotron radii of motion are smaller than the transverse size of the ion channel. At a radius channel about $R \ddot{y} 10\,A^{\circ}$, the speed which can be estimated from the formula for cyclotron motion in a magnetic field of the order of the Earth's field, ÿ 50 ÿT,

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there should be at least

$$U \ddot{y} R \frac{q}{M} B \ddot{y} 10 \ddot{y} 7 \text{ m/s}.$$

for the potassium ion and forty times more for the hydrogen ion. Can ions have such low speeds when entering the channel? Average thermal velocity potassium ion at T = 300 K about

$$U \ddot{y} \frac{\overline{kT}}{M} \ddot{y} 102 \text{ m/s}.$$

Even if the said ion is placed inside a channel of length L ÿ 50 A^{o}, the uncertainty of its velocity, according to the Heisenberg relation, will be more than

$$U \ddot{y} \frac{}{ML} \ddot{y} 0.3 \text{ m/s}.$$

Accordingly, the speed of the ion will be no less important, is far from consistent with the assumption on which the model is built.

The idea of the model is attractive, but eliminating the mathematical inaccuracies does not save it. The equation for the Lorentz force is hardly applicable. To describe ions confined in motion by the scale of an ion channel, such ions are waves rather than particles, despite their relatively large mass, see p. 267.

3.7.3 Ion cyclotron resonance

There is another, broadly speaking, interpretation of the topic in the literature. cyclotron resonance. It is known as "ion cyclotron resonance" (ICR). ICR appeals, on the one hand, to the fact that ions participate in magnetoreception, and, on the other, to the coincidence of effective frequencies with the frequencies of the cyclotron series. In this broad sense, the idea of cyclotron resonance is undoubtedly correct and useful, since as is based on more or less reliably established experimental data. In this sense, ICR is also a prototype of more advanced models that have not yet been created, which will satisfy all criteria of scientific methodology. It is important that the broad interpretation of the topic cyclotron resonance leaves room for specific implementations of this idea. One interesting proposal is the impact on the ion of internal, or endogenous electric fields, [525]. They are constantly present in the body due to the occurrence of various

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biochemical processes with charge transfer. Libow believes that such fields may have complex frequency spectra, in particular
can excite ions at characteristic frequencies of the cyclotron series.
This makes it possible to interpret the biological effects of weak constant magnetic fields. In an altered magnetic field, cyclotron frequencies change, so that the pattern of their "superposition" on the frequency spectrum also changes.
endogenous electric fields. In turn, a change in the excitation mode of ions occurs. It is difficult to test this hypothesis at this time,
To do this, it is necessary to measure the spectra of endogenous fields simultaneously with the MBE.

3.7.4 About the width of the resonance-like response

From Fig. 3.11 it is evident that there is a certain resonance width due to the limited measurement time T. Such broadening exists even in the absence of attenuation factors. The width of the peak or maximum
is approximately equal to ÿ=2ÿ/T . In the ideal case of infinite measurement time T = ÿ the width becomes equal to zero, as well as
should be for an ideal oscillator without damping.

Attenuation, or relaxation, is often taken into account *phenomenologically,* by introducing into the equation of particle motion an additional friction force proportional to the velocity, for example the term ÿU/ÿ on the right-hand side of equation (3.24). This leads to an additional factor of broadening the resonance curve.

It is not obvious in advance which of the two broadening factors will predominate. In magnetobiology experiments, the measurement time T is not
is completely controlled by the experimenter; it cannot be made arbitrarily large. The role of the measurement time limiter is transferred to the biological system being studied, or more precisely, to the biochemical processes involved in the interaction with the particle—

primary target of the MP. The measurement time T here should be understood as the characteristic coupling time during which a biophysical or biochemical system “allows” the primary oscillator, receptor
MP, to accumulate MP energy or, more generally, to be
in a state consistent with the MP in phase; we can talk about time
coherent interaction of a particle with an MF.

The characteristic time of development of biochemical processes, from shares seconds to minutes can obviously have a significant impact on the width
observed frequency responses in the low-frequency range when
the order of magnitude of the frequencies under study is comparable to the characteristic frequency T ÿ1. This circumstance is often overlooked. For example, in

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[527, 519, 320, 125] discuss the resonance width only in connection with the damping factor, the attenuation of the oscillator oscillations.

In the case of a sufficiently long measurement time, the shape of the resonance curve or the dependence of the power of forced oscillations, that is, — the square of the amplitude of oscillations y, from the frequency ÿ of the external force, has form

$$y2 ÿ ÿ2 + aÿ+ b \quad ^{-1} \quad ,$$

where a and b are coefficients. A similar Lorentzian form is also found for the amplitude of resonant transitions of a quantum system, see Fig. 4.19. [374] tried to show that the frequency dependence contour of the experimental MBE peak in Fig. 2.24 (at five fixed frequency values) has the shape of a Gaussian distribution. According to the authors [374] It is precisely this form that should appear in the spectral peak of the MBE, since the latter is a collective response of an ensemble of individuals resonating systems with random scattering of parameters. Note that however, that five points, located more or less symmetrically relative to the maximum, as in Fig. 2.24, it would be possible with equal successfully approximated by many other functions, including the Lorentzian form and the interference motif (sin x/ x)2.

■ There are no known works where the width of the spectral maxima of the MBE would be interpreted differently than the damping of classical oscillators or resonant quantum transitions. However, uniaxial magnetic field does not induce resonant transitions in the states of the Zeeman multiplet. Accordingly, in such cases, due to the absence of resonance, the concept of resonance width loses its meaning. At the same time, the broadening of spectral maxima due to the limited time of coherent interaction, or coupling time, is of a general nature and manifests itself independently of the physical nature of the spectrum of maxima.

3.8 Parametric resonance in magnetobiology

3.8.1 Parametric resonance of a free particle in MP

The process of binding of ions or macromolecules to their receptors, based on the classical dynamics of a particle in a magnetic field, was studied by Chiabrera, Bianco et al. [409]. In a constant magnetic field, the motion of a free particle is finite; on average, over time, no displacement of the particle occurs. Studied

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case of parallel orientation of constant and variable magnetic fields

$$H = HDC + HAC \cos(ÿt) .$$

It is shown that if the frequency of the alternating magnetic field is the n-th subharmonic cyclotron frequency of the particle, the magnetic field causes a constant component in the particle's displacement. This, according to the authors, affects the probability of ligand binding to the receptor. The displacement is obtained in the form
some combination of Bessel functions of order n, n +1 and n ÿ 1.
It is noted that if n =1, that is, the field frequency is equal to
cyclotron frequency, then the first *zero* of the response function occurs at
a certain ratio of the amplitude of the alternating to the constant MF HAC/HDC ÿ 1.85,
maximum at HAC/HDC ÿ 0.9. Application of this model to the Ca2+ ion made it possible to compare the model and Blackman's experimental data on MBE obtained at different frequencies
and with different HAC/HDC ratios. Apparently, this was the first,
Although far from perfect, the model of magnetically sensitive communication
ions.

Let us present the derivation of the relation for the velocity, and not for the displacement ion, in the notation adopted in this book, and in a somewhat simpler way than in [409]. In the mentioned work, the motion of an ion in the xy plane in an MF H ÿ z was considered, in the limiting case of very small attenuation. We write the equations of motion of a particle under the action of
Lorentz forces in coordinate form, x and y below are the velocity components,

$$xÿ = f + gy , yÿ = ÿgx , f = qE(t)/M , g = qH(t)/M c , (3.28)$$

where the electric field is directed along the x-axis. Mathematically, (3.28) is a system of Hill equations, and its singular solutions are parametric resonance.

The implicit assumption used in [409] was that the region of particle motion is small compared to the dimensions of the source of the uniform magnetic field. Only in this case can one assume that the induced electric field acting on the particle does not depend on the coordinates of the particle (see Section 1.4.1), which is reflected in the notation of the equation

(3.28). Without loss of generality, we can assume that the field E is directed
along the x-axis and having a magnitude

$$E = \frac{R}{c}\frac{dH}{dt} .$$

Here R is a constant of the order of the size of the magnetic field source, the scalar potential of the field is set equal to zero.

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Solution (3.28) can be easily found by the method of variation of constants. We write the equations in matrix form

$$u\ddot{y} = Au + B,\ u = \begin{matrix} x \\ y \end{matrix},\ A = \begin{matrix} 0 & g \\ \ddot{y}g & 0 \end{matrix},\ B = \begin{matrix} f \\ 0 \end{matrix}. \quad (3.29)$$

There are two linearly independent solutions of the corresponding homogeneous, that is, for B = 0, equation:

$$u1 = \begin{matrix} \sin w \\ \cos w \end{matrix},\ u2 = \begin{matrix} \cos w \\ \ddot{y}\sin w \end{matrix},\ w = g\,dt.$$

We seek the solution (3.29) in the form u = c1u1 + c2u2. Substituting it into this equation, we find a system of equations for the coefficients c:

$$c\ddot{y}1 \sin w + \ddot{y}c2 \cos w = f,\ c\ddot{y}1 \cos w - \ddot{y}c\ddot{y}2 \sin w = 0,$$

which has an obvious solution $c\ddot{y}1 = f \sin w$, $c\ddot{y}2 = f \cos w$ or

$$c1 = f \sin w\,dt,\quad c2 = f \cos w\,dt. \quad (3.30)$$

From the form of u it follows that the velocity components can be written in the form

$$x = c1 \sin w + c2 \cos w,\ y = c1 \cos w - \ddot{y}\, c2 \sin w.$$

Then we find that the square of the velocity modulus is equal to $v2 = x2 + y2 = c2\,1 + c2\,2$. This can also be written as the sum of the squares of the real and imaginary parts of the complex coefficient

$$v2 = 2\{c\} + 2\{c\},\ c = feiwdt. \quad (3.31)$$

Integrating g, we obtain

$$w = g\,dt = 2\ddot{y}0t + 2\ddot{y}1 \sin(\ddot{y}t)/\ddot{y},$$

where $\ddot{y}0$ and $\ddot{y}1$ are the Larmor frequencies associated with the HDC and HAC fields, respectively. Hence, substituting into (3.31), introducing the notations $z0 = 2\ddot{y}0/\ddot{y}$, $z1 = 2\ddot{y}1/\ddot{y}$, and using the relation

$$eiz \sin \ddot{y} = \sum_n Jn(z)ein\ddot{y},$$

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we find, by calculating f = ÿ2ÿÿ1R sin(ÿt), after simple transformations, the coefficient c in the form

$$c = \ddot{y}2\ddot{y}1R \sum_{n} Jn(z1) \sin \ddot{y} \; ei(z0+n)\ddot{y}\, d\ddot{y} . \qquad (3.32)$$

The integral is found by repeated integration by parts.
He is equal

$$\frac{i\ddot{y} \sin \ddot{y}\, \ddot{y} \cos \ddot{y}}{1\ \ddot{y}\ \ddot{y}2} \; ei\ddot{y}\ddot{y} \;,\ddot{y} = z0 + n.$$

We will not take into account either the finiteness of the observation time of the system or the initial conditions, since our goal is only to illustrate the general nature of the response. The expression for the integral shows that under resonance conditions, ÿ = ±1, the coefficient c, and with it the particle velocity, increase without limit. It is evident that the terms of the sum in
(3.32) decrease rapidly with increasing number n due to the properties of the integral. For We will limit our assessments to taking into account two members that provide the maximum contribution, with numbers n, which follow from the equalities z0+n = ±1. Then the real
and the imaginary parts of the coefficient c are equal

$$\{c\} = \ddot{y}\ddot{y}1RJn(z1) \sin2\ \ddot{y},\ \{c\} = \ddot{y}1RJn(z1)(\sin \ddot{y} \cos \ddot{y}\ddot{y}\ddot{y}),\ddot{y} = \ddot{y}t.$$

Accordingly, the square averaged over a large time interval
speed is written as

$$v2 = \ddot{y}2\ 1R2J2\ n(z1)\sin4\ \ddot{y} + \sin2 \qquad \ddot{y} \quad \cos2\ 2\ \ddot{y}\ddot{y}\text{-}\sin\ddot{y}\ddot{y} \cos \ddot{y} .$$

The contribution of the first two terms is equal to 1/2, the contribution of the last term is equal to zero. The contribution of ^{2} reflects the unlimited increase in speed in
the term ÿ under resonance conditions z0 + n = ±1 in the absence of damping.

Of interest is the part of the mean square velocity that is non-trivially dependent on the amplitude of the magnetic field. Let us agree to call it the magnetically dependent part. It is equal to

$$v2\ddot{y} \qquad \frac{1}{2}\ddot{y}2\ 1R2J2\ n(z1) .$$

For a fixed constant magnetic field, the resonance frequency (parametric), following from the relation z0 + n = ±1, is equal for the two indicated terms (3.32) ÿ= ÿ2ÿ0/(1 + n) and ÿ=2ÿ0/(1 ÿ n). If the magnetic field frequency ÿ is chosen to be equal in modulus to the Larmor frequency, then the corresponding values of n are equal to 1 and ÿ1, and the values of the argument z are equal to

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ÿ2ÿ1/ÿ0 and 2ÿ1/ÿ0. However, since for real arguments and
integer n Bessel functions satisfy the equalities J2 n(ÿz)=J2 n(z)
and J2 ÿn(z)=J2 n(z), then both terms make an equal contribution to the mean square
speed. Since ÿ1/ÿ0 = HAC/HDC, then

$$v2ÿ \; ÿ2 \; 1R2J2 \; 1 \quad 2\frac{HAC}{HDC} \quad . \qquad (3.33)$$

This formula fully illustrates the complex dependence of speed on
parameters of the magnetic field. The fact that this function successfully
approximates the experimental data in Fig. 2.11 should apparently be considered
a coincidence. The magneto-dependent part of the square of the velocity does not exceed
in order of magnitude ÿ2 1R2. Consequently, the change in energy, precisely
its part, which depends polyextremally on the amplitude of the variable MF, does not exceed
dÿ ÿ MV dV where V is the velocity of the particle, ,
and dV = ÿ1R is the change in velocity under the influence of the induced
electric field. If we assume that the ion was initially moving with
thermal velocity, then the relative change in its energy, as easily
find, is limited by the value dÿ/ÿTÿ 10%. This might seem
interesting, if it weren't for the fact that at thermal speed
the region of ion motion of the order of the cyclotron radius in the geomagnetic
the field far exceeds not only the size of a biological cell, but
and a reasonable size R of the MP source. What does the given calculation do?
untenable due to the original recording of the equations, regardless of
the size of the biological system. Moreover, interaction with environmental molecules is more
likely to lead not to processes that can be described by phenomenological attenuation, but
to Brownian motion
ions. This leaves virtually no hope for the accumulation of a response
to the MP signal in any dynamic variable of the ion.

To circumvent this difficulty, Chiabrera and Bianco in [343] proposed to consider
the motion (flat) of a charged particle, an ion,
hormone, antigen, etc., in the binding site, where, according to the authors' concept,
the intensity of thermalizing collisions with water molecules is low due to their
displacement from the binding cavity by hydrophobic forces. However, the residence
time or "flight" of a free particle in
such a region is small and the mechanism under consideration does not have time
to be realized. After all, for the averaged velocity and displacement to be meaningful,
the averaging time must cover at least
at least several periods of cyclotron motion. At thermal velocities of the ion, the
radius of such motion is in any case much larger
sizes of the binding site. Metastable motion of the ion with ma-

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with non-thermal energy could occur inside some molecular cavity that protects from thermal disturbances. But then
the equations of free motion are not applicable.

The work [409] had its positive significance. For the first time it was shown that some parameters of charge motion, in particular of an ion
Ca2+, in a combined MP in a complex manner, in the manner of functions
Bessel, depend on *the ratio of the amplitude of the alternating and the magnitude of the constant magnetic field.* Obviously, the model is not applicable to real conditions of ion movement in biological structures. Despite
This, the presence of amplitude and frequency windows of the MF efficiency in the model, which corresponded well to the windows observed in the experiment, indicated the prospects of searching for MBE mechanisms associated with the dynamics of ions. Later, in the work [519], Lednev drew attention to the fact that such complex dependencies on the HAC/HDC parameter
arise from the scattering of optical radiation by an atomic system placed in a magnetic field. This occurs due to transitions in the quantum states of an electron bound in an atom. Lednev suggested that the dynamics of ions confined in the binding cavities of some proteins could also follow the laws of parametric resonance of an atomic system. This idea is discussed in Section 3.8.3.

Since the model [409] uses the equations of classical dynamics
to describe the motion of an ion on a micro scale, it is unable to describe part of the effects observed in the experiment. The model predicts response maxima at the cyclotron frequency and its subharmonics and not predicts peaks at harmonics and subharmonics of harmonics. Such predictions, as will be shown in Chapter 4, are given by the ion interference mechanism.

In [519], Lednev suggested that the magnetic field causes parametric resonance of the Ca2+ ion in a state bound to certain proteins (calmodulin, protein kinase C, etc.). Therefore, the magnetic field shifts the equilibrium of the reaction

protein(..) + Ca2+ ÿÿ protein(Ca2+)

and leads to the observed response. In the model describing the influence
MP on bound Ca2+, the author proceeded from an analogy with the phenomenon of parametric resonance known in atomic physics. The phenomenon consists in that when modulating the magnitude of the magnetic field with a frequency ÿ close to the time-averaged difference in frequencies ÿ of the Zeeman sublevels of the particle, the intensity of spontaneous luminescence excited by broadband electromagnetic radiation, usually in the optical range,

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is also modulated with frequency ÿ. The depth of this modulation reaches its maximum under the conditions ÿ= ÿ/n, n =1, 2, ...

The author postulated that the magnitude of the biological effect under the action of a magnetic field is approximately described by a formula for the radiation intensity or the probability of spontaneous radiative transitions of an ensemble of particles. The basis for this postulate was the similarity of the dependences on the amplitude of the variable component of the magnetic field - in some
magnetobiological experiments, on the one hand, and in formulas
parametric resonance atomic spectroscopy, on the other.

Libow guessed the connection between the experimental frequency spectra and the cyclotron frequencies of ions and therefore tried to use the theory of cyclotron resonance to explain the MBE. Lednev guessed the same way.
connection of experimental amplitude spectra with dependencies of the type
Bessel functions in atomic parametric resonance and tried to use this theory to explain the experiment. In the future,
the idea of parametric resonance in magnetobiology in various forms
has been discussed in the literature [236, 320, 421, 423, 88], but a unified point of view has not yet been reached [465, 597]. Apparently, this is due to the fact that the authors mentioned, with the exception of [88], used
in his reasoning, he gave an overly simplified mathematical illustration of the theory of parametric resonance in atomic spectroscopy.
The physical content of the effect remained somewhat on the sidelines. To understand the essence of the disagreement, it makes sense to reproduce the theory.
parametric resonance in atomic spectroscopy in a more complete manner
volume.

3.8.2 Parametric resonance in atomic spectro-scopia

Let's consider the so-called parametric resonance in atomic spectroscopy
[7], adhering, as far as possible, to the terminology and notations adopted in the indicated monograph. The main properties of this effect will be obtained using a simple example of a three-level atomic system in the field of exciting electromagnetic radiation, usually in the optical range, in a combined low-frequency magnetic field.

The idealizations that are commonly used are that

1) the exciting radiation is constant in time and has a constant spectral density in a certain sufficiently wide band
frequencies; spectral components are ÿ-correlated,

2) absorption and spontaneous emission of electromagnetic waves is

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independent processes,

3) the disturbance introduced by the wave is small, so that the population of the ground level can be considered unchanged, and the population of the excited levels is relatively small, 4) the excited level

is split in the magnetic field H(t) into a Zeeman doublet, Fig. 3.12, 5) Raman scattering is small. Let the state

of an electron in an atom be a superposition

of eigenvalues

states |k of the Hamiltonian H0

$$ÿ= \sum_k ck(t)|k .$$

The intensity of spontaneous emission from levels 1 and 2 to level 0 is determined by the populations of states, |ck| 2, as well as other elements of the density matrix

$$ÿnk = cÿ nck .$$

Since the amplitude of the electric field of the emitted wave during the transition from the basic state |n to the state |0 is proportional to the matrix element

$$E0n ÿ0|de|n ,$$

where d is the operator of the electric dipole moment of an electron in an atom, e is the polarization vector of the emitted wave, then the amplitude of the superposition of waves emitted from levels 1 and 2 is equal to

$$E ÿ \sum_n cÿ 0cn0|de|n ,$$

and the wave intensity I = EÿE is equal to

$$I ÿ cÿ 0c0 \sum_{nk} ÿnkGnk , \qquad (3.34)$$

where Gnk = 0|de|n0|de|kÿ is the so-called observation matrix. Note that this expression, in addition to the terms proportional to the population of levels 1 and 2, i.e., ÿ11 and ÿ22, which determine the constant part of the radiation intensity, also includes cross terms ÿ12, ÿ21, associated with the interference of waves emitted from levels 1 and 2. These terms create a contribution to the intensity that depends on the magnetic conditions.

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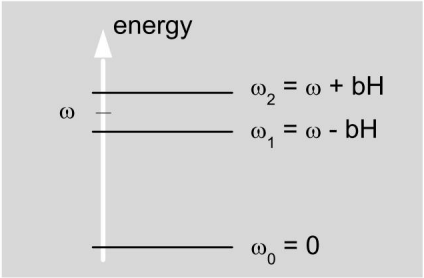


Fig. 3.12: Schematic diagram of the arrangement of energy levels of an idealized quantum system.
We.

Let the atomic system be placed in a broadband electric field.
magnetic radiation and the perturbation operator has the form

$$V = dE(t)\ ,\ E(t) = e\,E\ddot{y}\exp(\ddot{y}i\ddot{y}t\ \ddot{y}\ i\ddot{y}\ddot{y})\,d\ddot{y} + c.s. \qquad (3.35)$$

Here Eÿ and ÿÿ are the amplitude and phase of the spectral components, e is the polarization vector of the external radiation.

The dynamic equation for the density matrix, the quantum Liouville equation ih ÿˆ =[H0ÿˆ], written in matrix form in the representation |n, is

$$i\ddot{y}\ddot{y}\ nk = \sum_{m} [(H0)nm\ \ddot{y}mk\ \ddot{y}\ \ddot{y}nm\ (H0)mk] .$$

Taking into account the equality H0|n = ÿn|n, which can also be written as (H0)nm = ÿnÿnm, this leads to the equation for the matrix elements densities with coefficients ÿnk = ÿn ÿ ÿk:

$$\ddot{y}\ddot{y}\ nk = \ddot{y}i\ddot{y}nk\ddot{y}nk .$$

Taking into account the perturbation V and the phenomenological attenuation introduced with the additional term ÿÿnkÿnk the equation takes the form

$$\ddot{y}\ddot{y}\ nk = \ddot{y}\ (\ddot{y}nk + i\ddot{y}nk)\ \ddot{y}nk\ \ddot{y}\ \frac{i}{\hbar}\sum_{m} (Vnm\ddot{y}mk\ \ddot{y}\ \ddot{y}nmVmk) . \qquad (3.36)$$

Let us first consider the elements with n = 0, k = 0. Since there are no low-frequency components in the spectrum of V, the elements of Vnk are nonzero. only for transitions between the ground and excited states.
Then

$$\ddot{y}\ddot{y}\ 0k = \ddot{y}\ (\ddot{y}0k + i\ddot{y}0k)\ \ddot{y}0k\ \ddot{y}\ \frac{i}{\hbar}\sum_{m=1}^{2} V0m\ddot{y}mk + \frac{i}{\hbar}\ddot{y}00V0k .$$

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By virtue of postulate 3) the term ÿ 2 m=1 V0mÿmk can be neglected, and ÿ00 can be considered a constant. We have the equation

$$= ÿ (ÿ0k + iÿ0k) ÿ0k ÿ ÿÿ 0k \quad \frac{i}{—}ÿ00V0k .$$

Solution of the equation ÿÿ = fÿ + g(t), where

$$if = ÿ (ÿ0k + iÿ0k) ,g(t)= ÿ ÿ00V0k \quad — \quad , \qquad (3.37)$$

has the form

$$ÿ = eft C + eÿftg dt . \qquad (3.38)$$

Let us simplify the situation by setting the initial conditions such that C = 0. Since in (3.37)

$$V0k = v0k Eÿ exp (ÿiÿt ÿ iÿÿ) dÿ + c.s. ,v0k ÿ (de)0k , \qquad (3.39)$$

then the integral in the solution is equal to

$$\frac{ÿi}{—} ÿ00 exp (ÿ0kt + iÿ0kt) v0k Eÿ exp (ÿiÿt ÿ iÿÿ) dÿ + c.s. dt.$$

It contains the exponentials exp [i(ÿ0k ÿ ÿ)t] and exp [i(ÿ0k + ÿ)t]. The last rapidly oscillating term is unimportant, so after calculating the integral over time, we obtain

$$eÿftg(t) dt = \frac{}{ÿ0k + i(ÿ0k ÿ ÿ)} \quad \frac{exp \{[ÿ0k + i(ÿ0k ÿ ÿ)]t ÿ iÿÿ\} i ÿ00v0k Eÿ dÿ}{} ,$$

which after substitution into (3.38) gives

$$ÿ0k = \frac{i}{—}ÿ00v0kE \quad \frac{exp(ÿiÿt ÿ iÿÿ) dÿ . ÿ0k +}{i(ÿ0k ÿ ÿ)} \qquad (3.40)$$

From here we find

$$ÿn0 = ÿÿ \quad 0n = \frac{ÿi}{ÿ00vÿ 0nE} \quad \frac{exp(iÿt + iÿÿ) dÿ . ÿ0n ÿ}{i(ÿ0n ÿ ÿ)} \qquad (3.41)$$

In equalities (3.40), (3.41) it is assumed that the spectral density Eÿ = E is constant in the frequency range of interest to us. Now we consider the elements

of the density matrix for excited states n = 0, k = 0. In this case, from the sum over m (3.36) remains

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the only term m = 0, since the remaining terms contain factors Vmn = 0:

$$= \ddot{y}\,(\ddot{y}nk + i\ddot{y}nk)\,\ddot{y}nk\,\ddot{y}\,\ddot{y}\ddot{y}\,nk\,\frac{i}{-}(Vn0\ddot{y}0k\,\ddot{y}\,\ddot{y}n0V0k)\,. \qquad (3.42)$$

Let us introduce the notation

$$b\pm \ddot{y} \exp[\pm i(\ddot{y}t + \ddot{y}\ddot{y})]\,d\ddot{y} \quad , \quad c\pm \ddot{y}=0k \frac{\exp[\pm i(\ddot{y}t + \ddot{y}\ddot{y})]\,d\ddot{y}\,.\,\ddot{y}0k\,\ddot{y}}{i(\ddot{y}0k\,\ddot{y}\,\ddot{y})}$$

Applying them, we write expressions (3.39), (3.40) and (3.41) in the following view

$$V0k = Ev0kb\ddot{y} + E\ddot{y}\,0kb+ \,, \quad Vn0 = V\ddot{y}0n = E\ddot{y}\,0nb+ + Ev0nb\ddot{y}$$

$$\ddot{y}0k = \frac{i}{-}\ddot{y}00Ev0kc\ddot{y}\,0k\,,\ddot{y}n0 = \ddot{y} \frac{i}{-}\ddot{y}00E\ddot{y}\,0nc\ddot{y}n\,.$$

Now we can write the perturbation in equation (3.42)

$$\frac{i}{-}\,(Vn0\ddot{y}0k\,\ddot{y}\,\ddot{y}n0V0k)=$$

$$= \frac{E2\ddot{y}00}{2}\,2\,v0nv0kb\ddot{y}c\,\ddot{y}_{0k} + v\ddot{y}\,0nv0k\,b+c\,\ddot{y}_{\ddot{y}k} + b\ddot{y}c\,{}^{+}_{0n}\,.$$

The term (..) contains a rapidly oscillating factor, which we omit. The expression in parentheses of the second term is exp [i(ÿ t + ÿÿ)] exp [ÿi(ÿt + ÿÿ)]

$$\frac{\ddot{y}0k + i(\ddot{y}0k\,\ddot{y}\,\ddot{y})\exp[\ddot{y}i(\ddot{y}\,t + \ddot{y}\ddot{y})]\exp[i(\ddot{y}t}{+\ \ddot{y}\ddot{y})]\,\ddot{y}0n\,\ddot{y}\,i(\ddot{y}0n\,\ddot{y}} +$$

$$+ \frac{\ddot{y})\ \text{Since}\ \ddot{y}\ddot{y}\ \text{is a}\ \ddot{y}\text{-correlated random}}{\text{function of}}\ d\ddot{y}\,d\ddot{y}\,.$$

frequency, that is, ÿÿÿÿ ÿ ÿ(ÿ ÿ ÿ), the last integral reduces to

$$\frac{1}{\ddot{y}0k + i(\ddot{y}0k\,\ddot{y}\,\ddot{y})} + \frac{1}{\ddot{y}0n\,\ddot{y}\,i(\ddot{y}0n\,\ddot{y}\,\ddot{y})}\ d\ddot{y}\,.$$

Integrating[9] each of the terms using the equality ÿÿ(1 + x2)ÿ1dx = ÿ gives ÿ.
ÿ
Therefore, the perturbation in (3.42), called the pumping matrix, is

$$\frac{2\ddot{y}E2\ddot{y}00}{2}\,v\ddot{y}\,0nv0k\,\ddot{y}\,Fnk \quad , \qquad (3.43)$$

[9]Since the integration is within the limits (ÿÿ,ÿ), then, for example, the first integral does not depend on ÿ0k. It is reduced to the sum of the terms ÿ (ÿ2 + ÿ2)ÿ1dÿ and i (ÿ2 + ÿ2)ÿ1ÿdÿ, where the second term contains the product of an even and odd function under the integral sign and, therefore, is equal to zero.

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and in this case does not depend on time. Thus, the equation for
the cross terms of the density matrix has the form

$$\ddot{y}\ddot{y}\ nk = \ddot{y}\ (\ddot{y}nk + i\ddot{y}nk)\ \ddot{y}nk + Fnk\ . \tag{3.44}$$

Let us now turn on the modulation of the constant MF, so that the frequency of the Zeeman transition ÿnk, the parameter of equation (3.44), becomes a periodic function of time with the frequency of the external modulating
HAC fields cos(ÿt):

$$\ddot{y}nk = 2bH(t) = \ddot{y}0\ \ nk\ (1 + h\cos(\ddot{y}t))\ ,\ddot{y}0\ \ nk\ = 2bHDC\ ,h = \frac{HAC}{HDC}\ .$$

The derivation of equation (3.44) remains valid in this case due to the inequality ÿ ÿ0n. All quantities in equation (3.44) have the same indices, so it is convenient not to write them out. Now the equation
The nie looks like this

$$\ddot{y}\ddot{y} = \ddot{y}\ \ddot{y} + i\ddot{y}0\ [1 + h\cos(\ddot{y}t)]\ \ddot{y} + F. \tag{3.45}$$

Its solution is as follows

$$\ddot{y} = e^{\int g\,dt}\left[C + F\int e^{\ddot{y}}\, g\,dt\,dt\right],\quad g = \ddot{y}\ddot{y}\ \ddot{y}\ i\ddot{y}0\ [1 + h\cos(\ddot{y}t)]\ . \tag{3.46}$$

Let us introduce the notation

$$x = \ddot{y} + i\ddot{y}0\ ,z = h\ \frac{\ddot{y}0}{\ddot{y}} \tag{3.47}$$

and we find the integral in the exponent:

$$g\,dt = \ddot{y}xt\ \ddot{y}\ iz\sin(\ddot{y}t)\ .$$

Substitution into (3.46) at C = 0 taking into account the equality exp [iz sin(ÿt)] =
$\sum_n$ Jn(z) exp(inÿt) leads after simple transformations to the solution
zultata

$$\ddot{y} = F\sum_{nm} Jn(z)Jm(z)\ \frac{\exp\left[i(n\ \ddot{y}\ m)\ddot{y}t\right]}{x + in\ddot{y}}\ . \tag{3.48}$$

The radiation intensity (3.34) associated with the cross elements of the density matrix is proportional to

$$\tilde{}I\ \ddot{y}\ \ddot{y}12G12 + \ddot{y}21G21 = 2\ (\ddot{y}12G12)\ . \tag{3.49}$$

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Assuming G12 ÿ G exp(iÿ), using the formula

$$\frac{z1}{z2} = \frac{(z1)}{\cos(\arg z1 \ \ddot{y} \ \arg z2)\,(z2)}$$

and substituting (3.48) into (3.49), it is easy to derive the following relation

$$\tilde{I} \ \ddot{y} \ GF \underset{nm}{} Jn(z)Jm(z) \frac{\cos(n \ \ddot{y} \ m)\ddot{y}t \ \ddot{y} \ \arctan \frac{\ddot{y}0+n\ddot{y} \ \ddot{y}}{\bar{1}2} + \ddot{y}}{\ddot{y}2 + (\ddot{y}0 + n\ddot{y})2} .$$

This value experiences, as can be seen, maxima10 at the subharmonics of the unperturbed transition frequency

$$\ddot{y}max = \ddot{y}\ddot{y}0/n , \qquad (3.50)$$

proportional to the cyclotron frequency of the electron in the HDC MP.

On average, over a sufficiently large time interval T ÿÿ1, all time-dependent terms of the series, i.e., terms with n = m, disappear. The remaining terms create at the frequency of the main maximum ÿ= ÿÿ0

contribution

$$\bar{\tilde{I}} \ \ddot{y} \ GF \underset{n}{} J2 \ n(h) \frac{\cos \ddot{y} \ \ddot{y} \ \arctan \frac{\ddot{y}0(1\ddot{y}n)}{\ddot{y}}}{\ddot{y}2 + \ddot{y}02 \ (1 \ \ddot{y} \ n)2} . \qquad (3.51)$$

This series quickly converges, therefore the dependence on the relative amplitude of the magnetic field h is determined mainly, as can be seen from the denominator (3.51), by the term n = 1:

$$\bar{\tilde{I}} \ \ddot{y} \ J2 \ 1(h) . \qquad (3.52)$$

This expression reaches its first maximum at h ÿ 1.8.

Note that at the frequency of the first subharmonic ÿ= ÿÿ0/2 the denominator of expression (3.51) is equal to

$$\ddot{y}2 + \ddot{y}02 \ 1 \ \ddot{y} \ \frac{n}{2}^{2} \bar{1}2 .$$

Accordingly, the dependence on the amplitude, taking into account (3.47), is close to

$$\bar{\tilde{I}} \ \ddot{y} \ J2 \ 2(2h) \qquad (3.53)$$

10Here and below, if the index max is added to any symbol that denotes a frequency or magnetic field, this indicates the presence of a maximum effect at that frequency or at the specified magnetic field value. For other physical quantities, the index max denotes, as usual, the maximum value of that particular quantity.

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with a maximum in the region of h ÿ 1.5.

Relations (3.50) and (3.52) were the object of attention from the point of view of explaining the possible primary mechanism of some MBE. Similar dependencies were observed in experiments on the effect weak combined parallel MPs on biological systems. The works [519, 320] contain attempts to illustrate these relationships based on overly simplified reasoning, which leads to errors.

The shape of the dependence of ˜I on frequency in the region of maxima, that is, the shape of the spectral peaks, is determined mainly by the Lorentzian factor

$$ÿ2 + ÿ0 + nÿ \quad 2 \; - \; \tfrac{1}{2} \; . \qquad (3.54)$$

It is easy to find that the width of the maximum in order of magnitude is ÿ. On the other hand, the spectral peak at frequency ÿÿ0 will be resolved, if its width is at least less than |ÿ0|, that is, ÿ <ÿ0. The quantity ÿÿ1, as can be seen from equation (3.36), in its physical meaning is close to the lifetime of the excited states ÿ of the Zeeman doublet. This imposes certain restrictions on the lifetime of the excited states, which ensure the possibility of observing the effect, that is, changes in the intensity of scattered light in the experiment.

mente

$$ÿ> 1/ÿ0 . \qquad (3.55)$$

However, the concept of parametric resonance in atomic spectroscopy is connected precisely with the fact of modulation of the intensity of scattered light, and not with the modulation value, which is maximum at the Zeeman frequency splitting. Methods for recording the amplitude of a harmonic signal in physical dimensions are well developed, therefore the limitation (3.55) practically does not interfere with the observation of the fact of modulation, although it itself the modulation depth itself can be very small, for example 10ÿ3. Certain measures for the proper preparation of the atomic ensemble in in the form of a rarefied gas in a sufficiently strong magnetic field, they still accept it. The rarefaction of the gas ensures a long lifetime of the states, and strong MF - high splitting frequency of the Zeeman doublet, so that the ratio (3.55) is close to being fulfilled. If the possibilities The experiments are limited to observing the average intensity value; when the modulation oscillations are smoothed out, the limitation (3.55) becomes decisive.

The amplitude of forced oscillations of the density matrix elements increases at certain frequencies ÿ. From a mathematical point of view

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This is, by definition, a parametric resonance. From the point of view of
Physicists use the term "parametric resonance" in this
in this case there is a convention, but the correct meaning of the effect, as noted in
[7], is associated with parametric modulation of scattered radiation.
In relation to processes in quantum systems, the term "resonance" is used when there is a coincidence between the frequency of external radiation and the frequency of a quantum transition. In this case, the probabilities increase sharply
transitions, which manifests itself as an increase in the intensity of energy exchange
atomic system with an electromagnetic field - absorption and emission of electromagnetic waves.

In the case under discussion of broadband electromagnetic radiation incident on an atomic system, all optical transitions are saturated. The constancy of the pump matrix elements reflects precisely this circumstance. On the other hand, the integrated intensity of spontaneous emission in all directions is also constant. The effect of intensity modulation of re-emitted waves manifests itself when observing the atomic system at a certain angle determined by the observation matrix. The reason for the intensity changes is

in the interference of waves emitted from the Zeeman sublevels of the system.
A decrease in the radiation intensity in one direction is accompanied by an increase in radiation in the other direction, so that the total power of the scattered radiation is constant.

■ Thus, with parametric modulation of the intensity of scattered radiation, the intensity of the energy exchange of the atomic system with
electromagnetic field is constant and it is acceptable to talk about resonance
only in a certain conditional sense. Nothing changes in this sense even if we consider another factor of disturbance of the system. For example, thermal collisions of an atom with a thermostat with a high degree of accuracy
are reduced to a sequence of ÿ-shaped perturbations. Since they
have a continuous broadband spectrum in the frequency range under consideration, then the derivation of all relations is identical to the case already considered. Only with pulsed impact excitation should we speak of the constancy of the intensity of the energy exchange of the atomic system with
thermostat.

3.8.3 Ion parametric resonance

Knowing the essence of the phenomenon of atomic parametric resonance, it is easy to understand how justified its use is in magnetobiology models.

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Blanchard and Blackman [320] proposed to improve the formula [519] for the amplitude spectrum, since, as they note,
"Lednev's model contained some significant mathematical
errors and focused on a limited range of ions interacting with the Ca2+-binding protein." In doing so, the authors proceeded from
the same analogy with spectroscopic parametric resonance. Re-emitting electrons of atoms placed in a variable
MP and in the field of optical radiation were identified with ions enclosed in protein capsules and excited by thermal vibrations of the capsule walls.

The authors believed that uniaxial magnetic field causes a change in the populations of the ion's quantum states. This position is inaccurate. It was stated above
It is indicated that the change in the average radiation intensity in atomic parametric resonance exists only in certain directions. The integrated radiation intensity is constant, therefore, the populations of the emitting Zeeman levels are also constant; there is a dynamic equilibrium of populations. Under these conditions, it is impossible to talk about a change in populations or transition probabilities in MFs.

have to. Indeed, let us consider the population ÿnn of some
from excited levels, see (3.44). Since the frequency difference ÿnn =0,
the equation reduces to

$$\ddot{y}_{nn} = \ddot{y}\ddot{y}nn\ddot{y}nn + Fnn \quad , \qquad (3.56)$$

that is, it does not contain time-dependent parameters at all. The equilibrium constant value of the populations ÿnn(ÿ) = Fnn/ÿnn is determined by the balance of the pumping and relaxation factors and does not depend on the magnetic field.

The argument presented here “closes” those models built on the analogy with atomic parametric resonance, in which the magnitude of the bioeffect is associated with a change in the populations of quantum
states of the ion in an alternating magnetic field. The authors try to preserve the obvious positive aspects of the analogy, which consist in the similarity of the amplitude spectra, and suggest a connection between the bioeffect and another physical factor, the average intensity of spontaneous emission.
ion. There is an obvious illogicality here: the explanation of the biological action of low-frequency EMFs comes down to the assertion that
EMF of the radio range has such an effect.11 But its mechanism
We are also unclear today.

Further, the authors [320] expand the list of potentially significant
ions to atoms that form covalent bonds with protein structures.

11The order of frequencies of dipole transitions of an ion in a capsule is 1010 Hz.

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kov, V, Mn, Cu, Ni, Co, etc. This in itself makes sense, but when determining cyclotron frequencies, the authors assume the charges of these atoms to be equal to their valences [320, 421], which is not entirely justified. For atoms
forming ionic bonds, the charge is a well-defined quantity. For covalently bonded atoms, due to the strong redistribution of electron density, only the effective charge can be determined, which is significantly different (being expressed in electron

charges) from valence.

In addition, the authors also admit mathematical inaccuracies. However, it is precisely the conceptual difficulties, which, naturally, also exist in Lednev's work [519], that reduce the theoretical value of the proposed formulas for amplitude spectra. An important positive significance of the works [320, 421] is that attention is drawn to the presence of an array of experimental data, where the dependence of the bioeffect

from the ratio h = HAC/HDC at the point of maximum frequency ÿ corresponds to the function Jn(2nh), and not Jn(nh) as in [519].

The assumption that the magnitude of the biological effect under the action of a magnetic field is approximately described by a formula for the radiation intensity or the probability of spontaneous radiative transitions of an ensemble of particles was criticized in [236, 423]. The authors of the articles, not
delving into the theory of parametric resonance, they tried to prove that
thermal disturbances make the proposed mechanism inoperative at room temperature of 300 K. At the same time, they obviously assumed that the mechanism would be operational in the absence of thermal disturbances, that is, at 0 K. However, as we have seen, the mechanism
does not work regardless of the temperature factor. The arguments against, presented in these works, are based on the same illustrative ideas about atomic parametric resonance as the arguments
"for" the inventors of the model itself, and therefore equally unacceptable.

Adair [236] has long exploited the idea of the impossibility of magnetobiological effects, see [235], on the grounds that strict scientific
there is no explanation for these effects. However, to prove
the inconsistency of the explanations proposed in the literature, well-known and naive concepts of equilibrium thermodynamics, as applied to living systems, are used: the perturbation energy of the introduced magnetic field
one degree of freedom must be of the order of ÿT in order to observe,
effect; since this cannot be the case, any explanations of the MBE are doomed to failure. Such reasoning, despite its naivety, seems quite convincing to many.

Apparently, such criticism of the parametric resonance model

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ions in magnetobiology prompted Lednev to propose another explanation for the amplitude spectra of the MBE [125]. The new explanation appeals to the peculiarities of the motion *of a classical,* rather than quantum, particle in MP, although the name “parametric resonance” was retained by the author. from a mathematical point of view this is true, but to parametric resonance, stated earlier in [519], this work has no relation and, therefore, will be discussed in another section.

3.9 Oscillatory models

This section includes both classical and quantum models, which differ in that the motion of particles is limited to a certain region. space due to the action of forces, usually oscillatory potential.

3.9.1 Quantum Oscillator

Two related works by Chiabrera, Bianco et al. [621] were apparently the first attempt to consistently describe the processes of ionic bonding under the influence of collinear magnetic fields within the framework of quantum mechanics. They *formally* calculated the probability of transition between states ÿ0, ÿ—the wave functions of the ion outside and under the influence of a magnetic field. respectively. The probability of such a transition and the magnitude of the magnetic bioeffects according to the first work are interconnected. However, this This idea is inconsistent with the fact that the indicated magnetic field, acting only on the phase of the ÿ0 state, does not cause quantum transitions. The population of the state remains constant regardless of the magnetic field parameters.

Indeed, the angular part of the eigenfunctions of the central potential is described by spherical functions ÿ exp(imÿ). On the other hand, On the other hand, the interaction operator of a uniaxial magnetic field with the orbital magnetic moment of an ion is proportional to ÿ/ÿÿ. Therefore, the matrix elements of the operator in the plates of states with different magnetic quantum numbers contain a factor

$$\text{eimÿ}\left|\frac{\ddot{y}}{\ddot{y}\ddot{y}}\right|\text{eim ÿÿ ÿmm} \quad ,$$

such an operator only shifts the levels depending on the magnetic number m (Zeeman splitting). If we take into account states with different orbital number l, then the parity selection rules leave only transitions with a change in l by one. But such states

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have different parity; matrix elements of a scalar operator
interactions in states of different parity are equal to zero [122].

The idea behind this model is a quantum oscillator in a magnetic field. A uniaxial magnetic field does not "mix" the oscillator's states, therefore the amplitude of the oscillator's oscillations does not change.

In the second article, the authors suggest that the biological effects of MP are related to the probability of the ion being inside the speculative spheres highlighting the central region of the protein binding cavity. At the same time, no closed formulas were obtained for this probabilities. Note that this idea is close to the idea of interference quantum states of an ion in a protein cavity, which constitutes the main content of the book. The difference is that the interference mechanism takes into account the redistribution of the probability density over angular, not radial. This is important because angular redistribution, in comparison with radial, does not require energy costs gies.

3.9.2 Phase shifts of oscillator oscillations in magneto-thread field

In their works [277, 136], Belyaev, Matronchik, and Alipov proposed a mechanism to explain the effects of constant and low-frequency combined MF on living cells. The mechanism is based on two main postulates:

A) The target of MP in prokaryotic cells is the nucleoid, which performs the functions of the nucleus, which can be represented as a three-dimensional harmonic oscillator of the microwave range;
B) The electrical specific charge of a nucleoid changes according to the law

$$q(t)= q0(1 + \cos ÿqt),$$

where charge q0 and frequency ÿq are the model parameters. The authors start with equation for the Lorentz force in a uniaxial magnetic field—up to notation, it coincides with (3.24)—and obtains its approximate solution. Next, we consider the phase behavior of high-frequency oscillations oscillator when changing the magnetic field. The authors believe that if the phase change when varying the constant magnetic field on B is ÿ, 3ÿ and etc., that is, there is a change in phase to a state of antiphase, then such a change is accompanied by maximum bioeffect. Hence an expression follows for a number of quantities

$$B ÿ \frac{ÿq}{q0},$$

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which give extreme and zero effects. It is thus possible to achieve *qualitative* agreement with the experimental data of the same group of researchers, where cells were introduced into

area with changed field.

Let's take a closer look at the postulates of the model. The bacterial nucleoid cells is formed by the so-called bacterial chromosome, a single circular DNA molecule assembled into a compact “nucleus” of about 103 A in size
° A coiled DNA strand has many degrees of freedom and resides in the cell's cytoplasm, changing its shape. Is it then acceptable to consider the flexible strand as a point mass with 2–3
degrees of freedom?

The nature of the forces that provide the oscillatory potential is unclear.
for the center of mass of a nucleoid with high-quality microwave characteristics resonator. The stiffness c of the oscillator "spring" can be easily found by substituting the solution x = exp(iÿt) into the pendulum equation Mx¨+cx =0. Since the molecular mass of the *E. coli* nucleoid M ÿ 109 amu, the stiffness "spring" of an oscillator with a frequency of ÿ ÿ 2ÿ · 50 GHz would be equal to

$$ÿ2M ÿ 105 \text{ kg/s}2 . \quad (3.57)$$

This is a very stiff spring. For example, it is two orders of magnitude stiffer than a hydrogen–oxygen covalent bond.

If we nevertheless assume as a working hypothesis that the nucleoid is this is a mass with three degrees of freedom on a spring with stiffness (3.57), then the thermal amplitude X of the oscillations of the center of mass, as follows from the relation ÿ2MX2 ÿ ÿT, would be

$$X ÿ 10ÿ14 \text{ A}^{\circ} .$$

This is too small a value even for micro scales.
Thus, postulate A) of the model is hardly admissible. With regard to postulate B), we note that its presence is mandatory for the model, since in the final expression for fields B, which cause extreme

The MBE includes the parameters ÿq and q0 of the postulate. However, it is insufficiently substantiated. It is unclear why the charge of a large macromolecule as a whole can change so dramatically and regularly.

Finally, the very connection between the bioeffect and the phase change of high-frequency oscillations is not indisputable. In fact, the authors implicitly assume that the oscillating nucleoid remembers the phase state of high-frequency oscillations and stores this information over time.
The exposure time in the changed MP is several minutes in the experiment.

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Such temporal coherence can be realized in an unrealistic way.
high-quality oscillator

$$Q \ddot{y} \ddot{y}Te \ddot{y} 1013 .$$

Which indicates that the assumption is questionable.

The advantage of the model is that it shows the subtle relationship between the phases of the oscillator's oscillations and the magnetic field. This idea is valuable to understand the possible mechanisms of magnetoreception. It does not involve resonant energy transformations, which in any
in the case of activation by magnetic fields, will be incomparable with the thermal scale ÿT .

3.9.3 Parametric resonance of classical oscillator

Lednev's work [125] develops the idea of parametric resonance in a direction that is not related to parametric resonance in atomic spectroscopy.

The author considers the ion as a classical particle and the polarization of ionic oscillations in the protein. According to this idea, which repeats the main assumption of the work [384], the change in activity
calcium-binding proteins in alternating magnetic field is caused by a change in the degree of polarization of ion oscillations in the binding center inside
squirrel. This idea is attractive, but its implementation in the form of a specific mathematical model had shortcomings.

Firstly, in [25] it is shown that the movement of ions in microscopic volumes such as an ion channel or a protein binding site is unlikely
can be described classically, as is done in [125, 384], and not in a quantum way. Secondly, there is the following mathematical inaccuracy. The content of formula (17) of the original article [125]

$$p = A2\overline{}_X \ddot{y} \overline{A2}_Y \quad / A2\overline{}_X + \overline{A2}_Y \tag{3.58}$$

taking into account formulas (12, 13) of this article for the squares of the oscillation amplitudes

$$A2_X = 2A2 \cos2 \ddot{y}(\sin \ddot{y}t \ddot{y} \sin \ddot{y}t0) \cos2 \ddot{y}L(t \ddot{y} t0) +$$
$$+ \sin2 \ddot{y}(\sin \ddot{y}t \ddot{y} \sin \ddot{y}t0) \sin2 \ddot{y}L(t \ddot{y} t0)$$

and the notations adopted in the article

$$\ddot{y} = \ddot{y}L/\ddot{y} , \qquad \ddot{y}L = qBAC/2m,$$

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is reduced to a functional dependence for the desired degree of polarity.
zations

$$p = p(ÿ,BAC) ,$$

where ÿ is the frequency of the alternating component of the magnetic field with amplitude BAC. Note that here p does not depend on the magnitude of the constant field BDC. Further, as the author claims, by transforming formula (3.58) and averaging over time, he obtained an expression for the polarization of ionic oscillations

$$p = J2\,0(2ÿ)\,\frac{1}{1+ÿ2_{c}\,^{2\,ÿ}} + \qquad (3.59)$$

$$+ÿ \sum_{n=1} J2\,n(2ÿ)\,\frac{1}{1+(nÿ\ ÿ\ ÿc)2ÿ\ 2} + \frac{1}{1+(nÿ+ÿc)2ÿ\ 2} ,$$

which coincides with what is known from other literary sources
formula for the polarization of radiation re-emitted by the ensemble
atoms. Formula (3.59), however, taking into account the author's notation ÿc = qBDC/m, is reduced to a function of three variables

$$p = p(ÿ,BAC,BDC) .$$

Averaging usually does not produce new variables - is there a connection?
between formula (3.59) and the postulates of the model? The author actually returns to the analogy with an ensemble of coherently emitting atoms in MP, since formula (3.59), as he notes, describes the degree of polarization of the radiation of atoms.

In [88], Zhadin considered the classical oscillatory dynamics of a molecular system of ligands binding a protein cavity and a bound ion under the action of thermal perturbations. This problem had been posed many times previously. In [409, 343], Chiabrera obtained analytical expressions for the average ion velocity, which have an extremal character at a number of selected frequencies and amplitudes,
It was not possible to achieve good agreement with the experiment. Mehsam and Pilla [581] performed a numerical integration of the dynamics of an ion oscillator in a coupling cavity, but the frequency and amplitude spectra were not considered.

The results [88] are reduced to two verbal statements, one of which is which is that parametric resonance is unlikely
ion, understood in its orthodox sense, as an increase in the energy of a particle with modulation of the magnitude of the magnetic field - the parameter of the corresponding equations. Constructive and, in a sense, opposite

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the claim was that at frequencies of magnetic fields such as Larmor or cyclotron frequencies, a redistribution of energy could occur
thermal fluctuations of the ion-environment system and the growth of thermal ion energy by several degrees.

The proof begins by writing down the equations for the Lorentz force in Cartesian coordinates. Here is one of the equations for the x-coordinate:

$$\frac{d2x}{dt2} + ÿ \frac{dx}{dt} + ÿ2\ 0x\ ÿ\ 2ÿL(1 + ÿ \cos ÿt) \frac{dy}{dt} + ÿyÿLÿ \sin ÿt = = \sum_{k} Ckx \cos(ÿkt + ÿkx) .$$

Here the first and third terms correspond to a normal harmonic oscillator with natural frequency ÿ0, the second to damping, the fourth
and the fifth one is the forces from the alternating magnetic field, the right-hand side is the Fourier expansion of random forces from the surrounding particles. The form of the equation is not indisputable.

1) The same dynamic factor, the interaction of the ion with thermal vibrations of the ligands, is taken into account in the equation twice: as phenomenological attenuation proportional to the rate of change of the coordinate, and as external forces on the right-hand side of the equation. Note that
phenomenological attenuation is an averaging of the action of external forces, therefore the coefficient ÿ is associated with the correlation function
external forces, as in the Langevin equation. This connection is omitted here.

2) Phenomenological attenuation as an averaging of microscopic forces is usually introduced for macroscopic bodies, the physically infinitely small interval of motion of which includes a sufficiently large
number of collisions with the medium. This is unlikely to apply to an ion in a binding cavity.

3) A random external force is represented by a series, not an integral
Fourier. At the same time, no grounds have been formulated for considering a random force a (quasi)periodic function.

4) The fifth term of the equation, according to the author, is the vortex force electric field resulting from changes in magnetic field during
time. A well-defined quantity in a homogeneous variable
MP is the rotor of the electric field:

$$\text{rotE} = -\frac{1}{c}\frac{ÿH}{ÿt} .$$

It is impossible to obtain an expression for E from this equality without taking into account additional conditions. To calculate the force acting on the charge

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in a variable homogeneous magnetic field, that is, the electric force from such a field, it would be necessary to integrate the forces from all elementary sources of these magnetic fields, somehow located in space
relative to the charge. In the case under study, the author implicitly used
the condition that the center of the ion coordinate system coincides with the center of the axially symmetric system of magnetic field sources. It is easy to see now,
that this condition will be satisfied, at best, only for a single ion from a given ensemble, and not for all ions in the ensemble. Therefore, the above-given notation of the vortex electric field forces does not have sufficient generality for subsequent analysis.12

Next, when moving to a non-inertial, non-uniformly rotating
The Coriolis force is lost in the equations for the Lorentz force in the coordinate system. The next statement—that in a rotating coordinate system, magnetic fields do not act on the ion—is inaccurate. It is based
on the Larmor theorem. According to the theorem, the behavior of a system of identical charges q with mass M, performing finite motion in a centrally symmetric electric field and in a weak uniform magnetic field H, is equivalent to the behavior of the same system of charges in the same electric field
field in a coordinate system uniformly rotating with angular velocity ÿ = qH/2Mc. The theorem is valid when the potential energy
system of charges, in the particular case of a single ion, is invariant to rotations of the reference frame [121]. This necessary condition is obviously not satisfied when taking into account additional forces that are present in the equation in the form of phenomenological attenuation or in the form of external forces.
Moreover, Larmor's theorem is true for constant MP. The possibility
its generalization to the case of variable MP has not been studied by the author.

Next, the transformed equation is reduced to the inhomogeneous Mathieu equation with a variable right-hand side, but the conclusion about its nature solutions are made on the basis of known solutions of the homogeneous equation Mathieu, that raises doubts.

A number of such omissions reduce the value of the result. Moreover,
It is unclear how it could be used or tested: none
functional dependencies on MP parameters have not been deduced.

12Note that this mistake is widespread. It is committed by both supporters and and opponents of the phenomenon of biological magnetoreception. Thus, a well-known specialist in the field of MBE criticism, Adair, in the note *Bioelectromagnetics, 19:136, 1998,* tried to justify the impossibility of the action of a weak low-frequency magnetic field on DNA in a cell. He used the formula E = ÿ(r/2c)ÿB/ÿt to estimate *the maximum* electric field in
cell of size r, induced by MP B. However, it is easy to see, see section 1.4.1, that
This is an estimate of the difference in fields at the edges of the cell, and not an absolute value of the electron. trigeminal field.

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The conceptual side of the matter is as follows: There is a pendulum excited parametrically by a very weak signal in the presence of a much more powerful additive random force. It is proposed the idea that at the resonant frequency the energy of the pendulum can increase significantly. However, even in the absence of noise and attenuation, in Under the most optimal conditions, the ion energy could change noticeably only after several months of coherent swing of such a pendulum, see section 3.10. Consequently, we could talk about the fact that The magnetic field controls the process of energy exchange between the ion and the random force source. But no mechanism has been proposed that would act "against" the natural tendency toward equal distribution of thermal energy. energy over all degrees of freedom.

The results of computer modeling presented in one of the subsequent works on this topic are also unconvincing. The noise factor in the time interval typical for the problem, on the order of seconds, is close to a ÿ-correlated random process with a spectrum near the characteristic microwave frequencies of ionic bonds. This factor is modeled a signal that differs from the real one in three, and at the same time the most essential positions. Firstly, a deterministic signal is taken, which eliminates averaging, which is very unfavorable for the results of the model based on random parameters of the noise signal; secondly, the signal is harmonic, which also excludes unfavorable time averaging; thirdly, the frequency of this signal is reduced by nine orders of magnitude compared to the real one, chosen to be comparable with the Larmor frequency. This led to preserving the relative phases of signals, "noise" and from the magnetic field, over the computer calculation time interval. Naturally, under such conditions, parametric resonance was observed.

■ The fundamental disadvantage of this and similar models is that that they “don’t work” even in the absence of noise factors and, therefore, are not capable of constructive testable predictions.

3.9.4 Models of enzymatic reaction

There are several proposals on the mechanisms of influence of EMF on enzymatic reactions. However, they are distinguished by relatively high frequencies of presumably effective EMFs.

Zubkus and Stamenkovich [94] considered the effect of EMF on biochemical reactions catalyzed by transferases, i.e. reactions in which an atom or group of particles is transferred from a substrate to a product. It was suggested that the reaction rate can change in a variable

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electric field due to the change in the diffusion rate and the probability of tunneling through the barrier along the reaction coordinate. The effective frequencies of the EMF in these mechanisms are of the order of their natural vibration frequencies of the transferred particle on the bond being broken. For example, this will be ÿ ÿ 1013–1014 sÿ1 for a proton on a hydrogen bond. There are no estimates of the effective amplitudes of the external field.

Belousov, Kovarsky et al. [195] considered a possible scenario changes in the rate of enzymatic reaction in EMF at physiological temperatures. An electron-vibrational model was used enzymatic reaction, when the adiabatic potentials have the form oscillatory wells along the generalized reaction coordinate. External EMF affects the probability of nonradiative dissociation of the complex product-enzyme. The effect of microwave fields on the reduction of the activation energy of the complex is considered. This model predicts the appearance of a trigger effect depending on the reaction intensity of the external field. At the same time, there is no assessment of the effective fields. It remains unclear Can windows of effective parameters appear in such a model? Apparently, the model is not applicable in the region of low-frequency magnetic resonance, since the mechanism of “coupling” the field to the quantum system is represented by the energy of the dipole moment of the complex in the field of the electric component EMP.

3.10 Magnetic response of particles with spin

The basis of any mechanism of biological action of EMF is the interaction of the field with matter, i.e. atomic nuclei and electrons.
The fundamental description of the interaction of electromagnetic fields with particles of matter with spin 1/2 is associated with the representation of the latter in the form of a Dirac spinor field. It describes, within the framework of quantum electrodynamics, electrons and, phenomenologically correctly, protons in the atomic scale.

The Lagrangian of the interaction of the EMF with the spinor field is established from the requirement of invariance of the theory with respect to the local phase transformation of the spinor field and has the form L(x)= eAÿ(x)jÿ(x) , where e is the electron charge, Aÿ =(A0, A) is the 4-potential EMF, jÿ is the particle field current. In the Hamiltonian semiclassical formalism, such a Lagrangian leads to a replacement of the momentum operator P on P ÿ eA/c. The speed of the particles that make up a biological system, much less than the speed of light and relativistic effects can be only minor adjustments to the relatively slow dynamics. Therefore,

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In the Dirac equation for the wave function of a particle in the electromagnetic field, a nonrelativistic approximation is used. To within terms of ÿ cÿ2, it leads to the equation iÿÿ/ÿt = Hÿ(r,s) with Hamiltonian

$$H = H(P, U) + H(P, A) + H(S, A) + H(S, P, A0),$$

where r, s are variables in the space of coordinates and spins. P, S are the momentum and spin operators, respectively. H(P , U) describes the dynamics of the orbital r degrees of freedom in some fixed potential U(r). H(P , A) gives the change in this dynamics under the action of EMF. H(S , A) determines the dynamics of the particle spin in EMF, finally H(S ,P ,A0) describes the interaction of spin and orbital degrees of freedom.

Already at this stage there are options for the mechanisms of action of EMF into orbital degrees of freedom. It is the latter degrees that determine the course of biochemical processes and indirectly control the behavior of biological systems. Obviously, the biological response to the action of an alternating magnetic field is ultimately determined by the absorption of the magnetic field energy, no matter how small it may be, and the transformation it, possibly through spin degrees, into the energy of orbital degrees freedom. The interaction of the magnetic field with possible collective excitations in biophysical systems is based on the interaction of the magnetic field with individual particles. Therefore, energy conversion processes or signal transformations in the dynamics of a single particle are the basis of the mechanisms of MBE. Signal transformation is limited to only two possibilities. The first is associated with the members H(P, U), H(P, A) and has classical analogy in the motion of a point particle in a certain potential under the action of the Lorentz force F = eE + e[vH]/c, where E, H — electric and magnetic fields. In this case, the energy of the magnetic field is converted either directly into the energy of the orbital motion of the particle, or in the redistribution of the particle probability density. In the latter case, the energy of the redistribution of the interference pattern is associated with by changing the number of EMF quanta, which requires, generally speaking, going beyond limits of the Hamiltonian semiclassical description.

The second, purely quantum, possibility is associated with the terms H(S , A) and H(S,P ,A0). This means that the energy of the magnetic field is initially is transformed into the energy of spin degrees of freedom, and then into the energy of orbital motion either by the "spin-forbidden" mechanism or due to spin-orbit interaction. The dynamics of spins manifests itself in interaction with orbital degrees of freedom. Therefore, the relatively weak interaction H(S ,P ,A0) could be significant.

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The study of quantum effects in a magnetic field usually begins with
magnetic Hamiltonian notations

$$H = \ddot{y}MH(t),$$

where the magnetic moment operator M depends on the type of the considered
systems. For example, for a one-electron atomic system it looks, in some approximation,
as follows

$$M = \ddot{y}B(L + 2S) + \ddot{y}I, \qquad (3.60)$$

where L, S are the operators of the orbital and spin angular momentum of the electron and
I is the spin operator of the atomic nucleus, ÿ = ÿ/I is the gyromagnetic ratio
nuclear spin, ÿ is the magnetic moment of the nucleus.

In most problems where the electron-nucleus interaction is unimportant, nuclear spin
is neglected, since the nuclear magneton is more than three orders of magnitude smaller
than the Bohr magneton. We will be interested in the motion of the ion as a whole particle
in some effective potential. The simplest idealization is the adiabatic approximation, which
is valid when the system contains fast and slow variables. Then the slow motion can be
described "adiabatically," that is, in a time-averaged or effective potential,

which is created by fast variables. In this case, the slow and
Fast dynamics relate to the motion of nuclei and electrons. The inner paired electrons of an
ion create an "elastic" atomic shell,
determining the effective radius of the ion, and the outer valence electrons binding the ion
to the ligands create an effective potential in which the ion moves as a whole. Experiments
on the interference of atoms in atomic beams confirm the appropriateness of the adiabatic
approximation in such cases.

To study the quantum dynamics of an ion in a magnetic field as a separate particle in
the effective potential, it is necessary to write down the magnetic operator
moment based on "first principles." It turns out that in this case
the energy of orbital motion of the ion as a whole is comparable to the energy
ion spin. The spin of an ion, due to the fact that the spin of the paired valence electrons is
zero, is equivalent to the spin of the ion's nucleus.

Thus, the problem of studying the dynamics of charged particles with spin in magnetic
fields arises. This problem has been studied repeatedly and in detail
has been studied in applications to various fields of physics, see, for example, [121]. In
relation to models of biomagnetic reception, the problem
has features that justify the assessment of these particular features.

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Hamiltonian of a particle with spin 1/2 in an external magnetic field taking into account the spin-orbital connection has the form, see, for example, [435, 10, 719]

$$H = \frac{(P \ddot{y} \quad \bar{q} cA)2}{2M} + \frac{qA0 \ddot{y}}{} 2\ddot{y}S\ H + \frac{2\ddot{y}2}{q} S\ (\ddot{y}A0 \times P) \qquad (3.61)$$

where ÿ, M are the magnetic moment and mass of the particle, A and A0 are the vector and scalar potentials of the electromagnetic field, H = rotA is the magnetic field, S is the spin operator, P = ÿiÿ is the momentum operator in the electromagnetic field. In a uniform MF, A = H × r/2, and in a central-symmetric potential of electrostatic nature Hamiltonian (3.61) can also be written as

$$H = \frac{P^2}{2M} + U(r)\ \ddot{y}\ (bL + \ddot{y}S\ )\ H + \frac{2\ddot{y}2}{q} S\ (\ddot{y}A0 \times P\ ) \qquad (3.62)$$

where b = q/2Mc is the charge/mass ratio of the ion, and the expression in parentheses is the operator of the effective magnetic moment of the ion, including the energies of the orbital and spin magnetic moments. Their contributions are comparable: the ratio ÿ/b = 2ÿM c/q is always in absolute value. greater than one. Therefore, spin effects in ion dynamics should, generally speaking, play a significant role. Dimensionless coefficient ÿM c/q, equal to the ratio of the NMR and cyclotron frequencies of the ion, appears quite often in formulas. A special term is introduced for it in the book. name "ion-isotope constant"

$$\ddot{y}= \ddot{y}c\ \frac{\ddot{y}N}{} = \frac{\ddot{y}Mc}{q}\ .$$

Its numerical values for different ions and different isotopes of their nuclei are given in Table 6.1 (Chapter 6).

From equation (3.62) it is evident that the energy of the magnetic moments of a particle in an MF is proportional to bH for the angular momentum and ÿH for the spin. In a variable magnetic field H sin(ÿt), it is easy to find the instantaneous rate of transformation of the magnetic field energy into the energy of, for example, spin: dÿ/dt ÿ ÿHÿ. This is a fairly small amount. It would take about 10 years to the ion has accumulated energy of the order of ÿT in MF ÿ 100 ÿT, ÿ 100 Hz at such conversion speed.

In reality, the situation is even more hopeless. Homogeneous The magnetic field does not cause quantum transitions. Therefore, on average over time the energy of the particle does not change. Quantum transitions under the influence of an alternating magnetic field occur: 1) when taking into account the spin-orbit interaction [26], 2) with a non-planar orbit [24], 3) in a non-uniform magnetic field.

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However, the contribution of these effects to the rate of energy conversion is still several orders of magnitude smaller.

■ Vanishingly small changes in the energy of a particle in an MF, associated as with both spin and orbital magnetic moment indicate that utilization of magnetic field energy in the MBE by accumulating it in any degrees of freedom is unlikely. It is advisable to search for alternative mechanisms that would not rely on energy, and on some other properties of the MP that distinguish it as a certain physical substance.

3.10.1 Weak and strong magnetic approximations fields

Despite its relative insignificance in some manifestations, spin-orbit interaction plays an important role in particle dynamics in weak MF. In the absence of MF, the spin-orbit interaction, no matter how small it is, means, under central potential conditions, the presence of a conserved total momentum J of the system, formed by the orbital and spin moments: J = L + S. This is evident

from the fact that in the central potential the Hamiltonian of the particle, in addition to the spin-orbit interaction under consideration, which in this case is proportional to the product LS, contains a term, dependent only on the radius r and the term proportional to the square angular momentum, ÿ L2. The product LS by all parts of , obviously commutes with the Hamiltonian. By virtue of the operator identity

$$J^2 = L2 + S^2 + 2LS ,$$

The operator of the square of the total moment also commutes with the Hamiltonian, which of the total , means that the corresponding physical element J is preserved. The projection momentum onto any axis described by the operator Jz. The wave functions of the system can be chosen as eigenvalues for all the specified operators and, accordingly, indexed by quantum numbers, radial n, the magnitude of the total momentum j and its projection m, and the orbital momentum l, then there are, functions |njlm.

A homogeneous magnetic field reduces the spherical symmetry of the system to axial. Additional terms of the Zeeman interaction of the orbital and spin magnetic moments with the magnetic field appear in the Hamiltonian. In this case, the spin-orbit interaction operator

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does not commute with the Hamiltonian, so the total momentum of the system is not conserved, and j is not a good quantum number.

If the magnetic field is large enough, spin-orbit interaction can be neglected. Then the spin and orbital magnetic moments interact with the magnetic field separately, the magnitudes of the orbital angular momentum and the projections of the orbital and spin angular momenta are conserved, and the appropriate eigenfunctions are the functions |nlmlms, defined by the azimuthal l and magnetic quantum numbers ml and ms. The splitting of energy levels in a relatively strong magnetic field, indexed by the same numbers, is called the Paschen–Back effect. The position of the levels is slightly modified by the spin–orbit interaction, considered as a perturbation.

In a relatively weak MF, one can, on the contrary, consider the Zeeman energy as a perturbation, and calculate the splitting as the diagonal elements of the perturbation in the plates of the unperturbed functions of the total momentum and its projection. A splitting of this type, indexed
quantum number j is called the anomalous Zeeman effect.
the normal Zeeman effect implies splitting in the MP
arbitrary value of the levels of a spinless particle.

Obviously, for particles with spin, the criterion for the applicability of wave functions of one or another symmetry depends on the possibility of neglecting spin-orbit interaction in comparison with Zeeman interaction. From
For comparison of two Zeeman energies, the smaller one must be taken. The ratio of splittings due to spin and orbital magnetic moments is equal to ÿN /ÿ0 = 2ÿ. Since the ion-isotope constant ÿ by
the absolute value is always greater than one, see Table 6.1, then the smaller is the energy of the orbital moment, equal in order of magnitude to ÿ0. The spin-orbit interaction operator has the form,
see (3.61),

$$Hso = S\frac{2ÿ2}{q}(ÿA0 \times P) .$$

In the central field ÿA0 =(r/r)ÿA0/ÿr. Therefore, we can write

$$Hso = \frac{2ÿ2}{qr}\frac{ÿA0}{ÿr}SL \quad ,$$

where L = ÿir ×ÿ is the dimensionless orbital angular displacement operator moment. The energy scale, that is, the spin-orbit interaction constant, follows the quantum mechanical averaging of the operator Hso, considered as a perturbation. Using the above

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operator identity, we obtain by order of magnitude

$$\frac{2\ddot{y}2}{q} \quad \frac{1}{r}\frac{\ddot{y}A0}{\ddot{y}r} \quad .$$

The potential A0 of an ion in a cavity is not completely determined. Apparently, a reasonable estimate of the mean in the last expression would be q/a3, where a is the radius of the cavity potential. We obtain the energy scale of the spin-orbit interaction in the form 2ÿ2/a3. To determine critical MP separating the regions of different approximations, let's equate the scales of spin-orbit and orbital angular momentum energies: 2ÿ2/a3 = ÿ0 = qHth/2Mc. From here, applying the definition of the ion-isotope constant ÿ = ÿM c/Sq, we find the critical field

$$Hth \ddot{y} 4\ddot{y}S\ddot{y}/a3 . \qquad (3.63)$$

It is easy to calculate, using Table 6.1, that for the values presented in In the table of ions with nuclear spin, the critical field varies in in the range of approximately 5–500 mT for cavities with an effective potential of radius 0.7 A^{o} For an electron in a “box” of radius 1 A^{o} from the corresponding wearing 2ÿ2 $_{B}$ /a3 ÿ eHth/2mec we would find the critical field in the region of 2 T, in full agreement with the known data of atomic spectroscopy. Of course, due to the unknown exact form of the ion potential in the cavity, this estimate is meaningful only in order of magnitude. However, It is no less clear that the geomagnetic field, one way or another present in In most magnetobiological experiments, it falls rather into the region of weak fields, in the above sense. Therefore, it is advisable to investigate both the strong field approximation and the approximation weak field, when the external magnetic field interacts with the total magnetic field moment of the ion.

3.11 Reactions involving free radicals

catch

The modes of reactions involving radical pairs (RP) are well studied, there are many works devoted to radical reactions in MP. Well-known reviews by Salikhov, Molina et al. [672], Buchachenko, Sagdeev and Salikhov [35], as well as Steiner and Ulrich [678] are A good introduction to the topic. Processes of magnetosensitive recombination of radical pairs may underlie the biological effectiveness of weak magnetic fields. This is a widespread and attractive idea.

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First of all, because these processes are practically independent of
ambient temperature. Therefore, the "kT problem" does not arise here. The frequency
and amplitude windows of the efficiency of the MF parameters with such a primary
mechanism of magnetoreception are associated with nonlinear
equations of chemical kinetics. A radical reaction is a sensitive link in a complex
biochemical system, which is described by nonlinear equations [568]. At the same time,
there are theoretical limitations on the MBE for such a mechanism. Perhaps for this
reason
the mechanism by which the biological effects of the magnetic field develop, as
both constant and variable, of relatively high intensity
> 1 mT.

3.11.1 Geminal recombination

Some organic molecules seem to consist of two relatively
strong and large parts, A and B, connected to each other by a single covalent bond. The
latter can be broken by thermal
disturbances: AB A+B. Due to the significant size of the particles and the viscosity of the
medium, the particles are unable to quickly disperse over a large distance and end up
as if enclosed in a "cage". A special state of the reactants arises, which cannot be
identified with any
product AB, nor with reactants A and B. The breakdown products of the AB molecule
appear as radicals Aÿ and Bÿ with an , molecules with an unpaired valence
electron. Therefore, the reaction is depicted as

AB Aÿ Bÿ A+ÿ Bÿ ,

where the intermediate state Aÿ Bÿ represents a radical pair (RP)
with unpaired electrons in the cell.

The spin state of the RP with half spins is described
singlet-triplet states with the following, accepted in chemistry
RP notations: S is a singlet state with zero total
spin, T is a triplet state with a total spin of unity. In the latter case, spin 1 can have
projections on the selected axis 1.0 and
ÿ1. These states are respectively designated as T+, T0 and Tÿ. The exchange interaction
of the electrons of the pair is essential, which
depends not only on the spin state of the RP, but also on the distance between
radicals, Fig. 3.13. The figure illustrates the terms of the RP in a relatively
strong magnetic field, when the spin and orbital magnetic moments interact with the
magnetic field separately.

It is evident that the stable state (recombination product) of RP is formed only in the
singlet state. At present, the details

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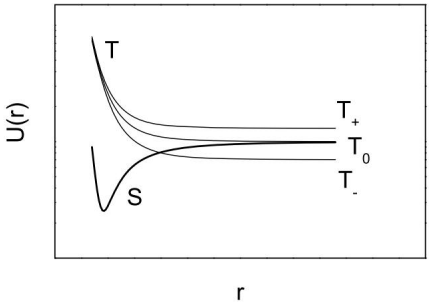


Fig. 3.13: Energy of the Coulomb interaction of the RP taking into account the energy of the exchange interaction in the singlet S and triplet T+,T0,Tÿ states

electron pair.

There is no clear description of the process of formation of AB from Aÿ Bÿ. Therefore, use a phenomenological description: it is assumed that the rate of formation of the product AB is mainly proportional to the probability (or
population, or intensity) of the singlet state of the RP. The formation of the product is accompanied by a decrease in the relative proportion of the RP
in the singlet state (chemical polarization of electrons - CPE).
Since the magnetic field in principle influences the evolution of the spin state RP, that is, causes singlet-triplet transitions, it is capable of changing the equilibrium ratio of free radicals Aÿ Bÿ and molecules ,
AB. It is believed that this could be one of the mechanisms of the IBE.

To describe the dynamics of the RP, a magnetic Hamiltonian is needed RP, which contains, in particular, the Hamiltonians of the magnetic moments of each radical. The magnetic moment operator M = (ÿ/S)S for
electron and the corresponding Hamiltonian have the form

$$M = 2\ddot{y}B\ S \quad , \quad H = \ddot{y}HM = \ddot{y}2\ddot{y}B\ HS\ .$$

However, in a weak MF the magnetic moment operator, see Section 3.10.1, should be written M = GJ where J is the total moment operator.
in a homogeneous MF Hz the magnetic Hamiltonian has the form H = GJzHz and determines the splitting of levels, see Appendix 6.2, multiple

$$\ddot{y} = \ddot{y}bgHz\ , \qquad (3.64)$$

where b = e/2mec, g is the g-factor (6.3). The active electron of the radical experiences the action of the effective molecular field (in the theory of solids bodies use the term "crystal field"). A chaotic precession of the electron's orbital momentum occurs, so that its average
the value is zero. The orbital angular momentum is said to be "frozen": L = 0. This means that the magnetic Hamiltonian contains

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only the spin operator: H = ÿSzHz. This Hamiltonian obviously splits the electron levels according to

$$ÿ = ÿHz .$$

Comparing this expression with (3.64), we find ÿ = ÿbg = ÿÿB g. Therefore, formally, the magnetic Hamiltonian of the electron of the radical is written put in the form

$$H = ÿÿB gHzSz . (3.65)$$

In an ideal situation of complete freezing of orbital momentum, substituting into (6.3) the values of quantum numbers for the electron i = 1/2, l =0 (formally, since L =0), j =1/2, ÿ=1, we find g = 2. In reality, the motion of an electron in a molecular field is not completely chaotic. Some small order, due to the specificity of the molecular field of a given type of molecule, remains. Orbital the movement of the electron in this case creates a small additional MP. It must be taken into account when calculating spin dynamics, [664]. In a fixed external magnetic field, the effect manifests itself experimentally as a small deviation of the g-factor from the ideal value of 2. This is the basis for the identification of molecular radicals by their spectra electron paramagnetic resonance (EPR).

Let us consider a simple model in which a molecule in a singlet spin state disintegrates as a result of thermal excitation. into a pair of neutral radicals. The simplest idealization is the so-called exponential model. It postulates a Poisson flow of output radicals from the cell. Accordingly, the lifetime of radicals in the cell is a random variable distributed according to an exponential law

$$f(t)= \frac{1}{ÿc} eÿt/ÿc , \quad (3.66)$$

where ÿc is the average lifetime of the RP in the cell, an important parameter of the model. The lifetime ÿc is of the order of ÿc ÿ R2/D, where the cage size for neutral radicals is R ÿ 10 A°, and the diffusion coefficient for inviscid solvents such as water, D ÿ 10ÿ5 cm2/s. That is, ÿc ÿ 10ÿ9 s.

At the initial moment of time, the RP is in a singlet state. In this state, radicals recombine at a certain rate K. External and internal magnetic fields cause singlet-triplet transitions. Since the spin selection rules allow recombination only from the S-state, the recombination rate, generally speaking, decreases. It is clear that if the rate of ST transitions is low, then the spin state of the RP does not have time to change during its lifetime.

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In this case, the recombination rate is equal to K and, obviously, does not depend from the magnetic field. In the opposite case of intense ST transitions, the correlation between the spins of the RP is quickly destroyed. The recombination rate then also does not depend on the magnetic field and is determined only by the average weight S-states with a random selection of spin states of radicals, then there is, K/4. Thus, there is a dedicated interval of MP, usually from units to hundreds of mT, when the statistical weight of the S-state has time change noticeably over a time of the order of ÿc, which leads to a dependence of the recombination rate on the magnetic field. The position of this magnetic field interval is obviously proportional to 1/ÿc and, in addition, depends on the nature of intracellular magnetic interactions. The latter determine the type of ST transition mechanism. Several such types are distinguished.

Relaxation mechanism. The spin state of the RP after its formation changes due to the relaxation of each of the spins to their equilibrium states. In general, the relative weight of the S and T states in the superposition changes, which indicates the presence of ST transitions. The relaxation time of the spins of neutral radicals in liquids with viscosity as

for water ÿ 1 cP is equal to 10ÿ7–10ÿ6 s, that is, much greater than ÿc. Therefore This mechanism becomes important, for example, in the cellular recombination of oppositely charged ion-radicals, for which ÿc, due to mutual attraction, can be significantly greater than 10ÿ9 s.

g-mechanism. After the formation of radicals, their spins precess, See Appendix 6.3, in a magnetic field that is a superposition of 1) the external magnetic field and 2) the field of the magnetic moments of the radical nuclei. Let the latter magnetic field be zero, that is, all radical nuclei are even and have no magnetic moment. Then the precession occurs in the external magnetic field with the Larmor frequency. It is proportional to the Zeeman splitting.
and, in general, is different for each of the radicals due to different g-factors:

$$\ddot{y}1 = \frac{1}{\ddot{y}B\, g1Hz}, \quad \ddot{y}2 = \ddot{y}B\, g2Hz\frac{1}{}.$$

The relative speed of dephasing, that is, the difference between these frequencies, makes up

$$\frac{1}{\ddot{y}B\, gHz}.$$

The influence of the magnetic field by the g-mechanism manifests itself when the magnetic field is large enough for the phase shift to be
a noticeable value, say, one radian. Then the order of the effective
The MP at g ÿ 10ÿ3 is equal to

$$H \ddot{y} \frac{}{\ddot{y}B\, g\ddot{y}c} \ddot{y} 105\ E.$$

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These fields are too large to reliably explain the MBEs that develop in fields of the order of 1 Oe and less.

Resonant excitation. If the precession frequencies of the spins of the RP differ, then by selecting the frequency of the external alternating field, it is possible to tune into the magnetic resonance of one of the spins. Its state is then will begin to oscillate with the Rabi frequency, ÿHAC = 2ÿB HAC/, thereby implementing ST transitions of the spin state of the RP. Dephasing of the order of unity occurs in fields HAC ÿ /2ÿB ÿc ÿ 100 Oe. Obviously, this mechanism of mixing singlet-triplet states does not is related to the effects of magnetobiology discussed in the book.

The HFI mechanism. The hyperfine interaction (HFI), that is, the interaction of electrons with the spins of nuclei, gives more optimistic estimates. For example, when one of the radicals has nuclei with magnetic moment, the precession of the spins of the radicals occurs in significantly different magnetic fields. Even if the difference in g-factors is insignificant, mixing RP or ST terms transitions still occur. Let the external The magnetic field is zero. The dephasing is approximately determined by the precession of the magnetic moment of only one electron of the pair in the magnetic field. moment of the nucleus, ÿ 100 Oe. Then, over the lifetime of the RP, the phase shift will be ÿB gHÿc/ ÿ 1, that is, a value sufficient for observation. Question whether an additional external magnetic field of the order of the geomagnetic field can significantly change the speed of ST transitions.

A relatively simple model, the influence of an external magnetic field on the recombination of a RP with one magnetic nucleus with spin 1/2 by the STV mechanism, has been studied many times [35]. In addition to the Zeeman energy of spins (3.65), the Hamiltonian of the model includes the exchange interaction

$$H_{exch} = \ddot{y}J(r)\ 1/2+2S\ 1S\ 2$$

with the constant J(r) and hyperfine interaction, in which, due to rapid chaotic rotations of radicals in the cell, usually leave only the isotropic part

$$H_{hf} = AS\ I \quad .$$

The spin Hamiltonian of the RP in the external MF H z has the following view

$$H = H0 + AS\ 1I \quad , \quad H0 = \ddot{y}\ddot{y}B\ gH\ S1_z + S2_z \quad \ddot{y}\ J(r)(1/2+2S\ 1S\ 2) \ , \tag{3.67}$$

where the g-factors are assumed to be the same for both radicals for simplicity and the Zeeman energy of the nuclear magnetic moment is neglected. It is known that the eigenfunctions of the Hamiltonian H0 are

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singlet-triplet states are formed, which in terms of single-particle spin states ÿÿ, eigenstates for the operator Sz, are expressed as follows

$$\ddot{y}m = \begin{cases} \ddot{y} & \ddot{y}1\,2\ddot{y}2 \qquad m = \ddot{y}1 \\ \frac{1}{\sqrt{2}} & 2\,\ddot{y}1\,1\ddot{y}2\,2 + \ddot{y}1\,2\ddot{y}2\,1 \qquad m = 0 \\ & 1\ddot{y}2\,2\,\ddot{y} \qquad\quad m = 1 \\ \frac{1}{\sqrt{2}} & \ddot{y}1\,2\ddot{y}2\,1 \qquad m = 2 \end{cases} . \qquad (3.68)$$

Here the first three basis vectors constitute a triplet Tÿ,T0,T+ symmetric with respect to particle permutations , the last vector is an antisymmetric state or singlet S. The range of variation of the index m = ÿ1, 0, 1, 2 is chosen so that for triplet states it coincides with the magnetic quantum number - the z-projection of the total spin S

1 + S 2. We denote the state of the nuclear spin by ÿÿ, so that the basis for studying the dynamic equation with Hamiltonian (3.67) will be the functions

$$\ddot{y}m\ddot{y} = \ddot{y}m\ddot{y}\ddot{y} .$$

Then an arbitrary state of the RP can be represented by a superposition

$$\ddot{y} = \sum_{m\ddot{y}} cm\ddot{y}\ddot{y}m\ddot{y} .$$

The indices denoted by Latin letters run through the values -1, 0, 1, 2 (2 for the singlet state), and by Greek letters - 1 and 2 (spin-down and spin-up states). The density matrix, the diagonal elements of which are the populations of the electron singlet-triplet terms, is determined by

they say it like this:

$$\ddot{y}nm = \sum_{\ddot{y}\ddot{y}} c\ddot{y}\,n\ddot{y}cm\ddot{y} . \qquad (3.69)$$

It is found by solving the equation of motion for the density matrix

$$i\ddot{y}\ddot{y}_{nm} = \sum_{k} [Hnk\ddot{y}km\,\ddot{y}\,\ddot{y}nkHkm] .$$

In some cases, it is assumed that the radicals of a pair are at a fixed distance from each other. Next, the population of the singlet state ÿ22(t) is found. The recombination rate p is assumed to be proportional to the time-averaged population of the singlet state. Since the lifetimes of RPs in a cell are distributed according to

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(3.66), then averaging is carried out with the specified exponential distribution.
division

$$p ÿ \quad \frac{1}{ÿc} \int_0^{ÿ} eÿt/ÿc \; ÿ22(t)\, dt .$$

In a more realistic case, along with spin dynamics, the spatial movement of radicals in the cell and their repeated contacts due to diffusion are also considered. The density matrix then depends not
not only on the spin variables, but also on the distance between the radicals r. Accordingly, the dynamic equation also changes. Spin
The effects of RP recombination taking into account the molecular motion of radicals are discussed in detail in the monograph by Buchachenko, Sagdeev and Salikhov [35].

An analytical study of the dynamics of the RP, even without taking into account molecular motion, is complicated by the fact that three-particle spin functions appear in the calculations. We will not present the solutions here.
for specific model situations. We will use approximate estimates and known results of numerical analysis of equations.

From equation (3.67) it follows that there are no significant changes in the spin dynamics should be expected when the scales of the Zeeman energy and the HFC energy are close, that is, ÿB gH ÿ A. The HFC constant is of the order
values of A ÿ 108–109 Hz, from which we find the corresponding scale
MP:

$$H ÿ \quad \frac{A}{ÿB\, g} \; ÿ 0.5–5 \text{ mT}.$$

Numerical calculations, see, for example, reviews [678, 35], show that
In most cases, the maximum changes in the recombination rate in the specified fields do not exceed one percent, with a characteristic lifetime of the RP of ÿ 10ÿ9 s. Assuming, very, very approximately, a linear field-effect relationship in the specified region, we find,

that in a geomagnetic field of ÿ 0.05 mT the effect will not exceed 0.1%. Experimental dependences of the rate of radical reactions in a magnetic field [462]
confirm this assessment. Brocklehurst and McLochlan in [329] in the model
with one magnetic core, we obtained by numerical methods ÿ 10% of the
change in terms of the geomagnetic field, but they used ÿc ÿ
2 · 10ÿ7 s. For normal values ÿ 10ÿ9 s and here we have 0.1%.

In [406] the so-called LFE (low-field effect) mechanism is considered, which can occur in MFs of the order of 1 mT due to slow oscillations of spin states in such a field. However, it is still unclear whether this mechanism is involved in magnetoreception of MF changes at

level of the geomagnetic field.

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■ Apparently, the value of 0.1% should be considered as an estimate of the maximum possible effects in the magnetic field of the order of geomagnetic due to the spin dynamics of the RP. Such an insignificant change in the rate of radical reactions implies the need for further "biochemical" enhancement. Grundler, Kaiser et al. considered
free-radical reaction as a link in a system described by a system of nonlinear equations of chemical kinetics [568, 497] with bifurcations. Small variations in the reaction rate could then cause significant, even qualitative, changes in the behavior of the biological system.

3.11.2 Characteristic experiments

There are indirect experiments that support the idea of radical pairs in magnetobiology. In [517], DNA mobility was measured in rat brain cells and a statistically significant 30% change was found of this parameter after two-hour irradiation of animals with microwaves at 2.45 GHz, 2 mW/cm2, in a pulsed 2 ÿs, 500 Hz mode. It is important that the injection of melatonin and other free radical scavengers blocked the occurrence of the biological effect of microwaves.

Other experiments, on the contrary, speak against the idea. [545] measured the rate of some enzymatic reactions in vitro, associated with coenzyme B12. The cobalt-carbon bond of the coenzyme can generate a spin-correlated radical pair. However, no significant dependence on magnetic field in the range of 50–250 mT was found for the two enzymatic reactions studied. The authors conclude that the effect of magnetic field on physiological processes is unlikely to be related to these enzymes.

Ho, Stone et al. [328] investigated the abnormal development of *Drosophila* fly larvae caused by 30-minute exposure to constant magnetic field. More than ten different parameters characterizing the morphological process during the first 24 hours of embryo development were measured. Figure 3.14 shows the dependence of the deviation index on the magnetic field magnitude. The range of constant magnetic fields, starting from 1 mT, in which significant changes were observed, indicates the probable mechanisms of the magnetic field's influence on free radical reactions.

In [363], Galvanovskis, Sandblom, and others measured the spectral power density of oscillations using a fluorescence microscope. concentrations of calcium ions in human T-leukocytes in the spectral range

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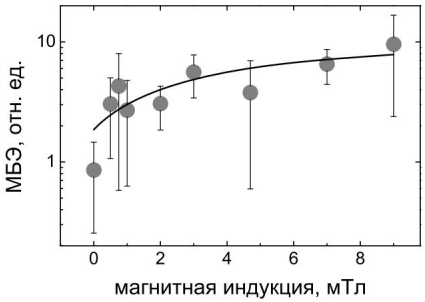


Fig. 3.14: Relative number deviations from normal development the larval stages of the fly exposed 30 min exposure at constant MP, according to [328].

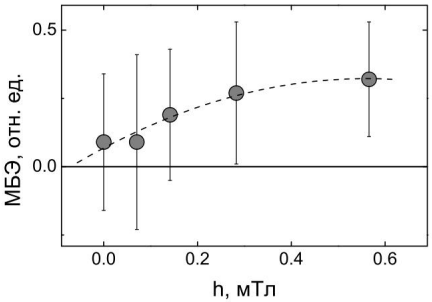


Fig. 3.15: Relative weight spectral density mask intracellular Ca oscillations in alternating magnetic field, according to data [363].

range of 0–10 millihertz. Magnetic circuit of the experiment

B(36)b(0–566)Bp(14)f(50)b50 Hz(< 0.2) ,

allowed us to evaluate the dependence of the measured parameter on the amplitude alternating magnetic field. Figure 3.15 shows the dependence on the field amplitude for the MBE, calculated as the difference between the control and experimental values in relation to the control. The scale of the magnetic fields causing changes is about 1 mT and the flat shape of the curve is characteristic of magnetosensitive radical reactions. Unfortunately, the data on the frequency
The selectivity of the observed effect is not given.

Lai and Carino [515] studied the cholinergic activity of rat brain tissue, the frontal cortex and hippocampus. They used 60 Hz MF of varying intensity and exposure duration. The authors suggested that a statistically significant effect is caused by

only those combinations of parameters where the product of the field intensity for the exposure time is quite large, Fig. 3.16. The data volume is small for reliable conclusions. For example, one can also assume that here too various physical mechanisms took place, interference in regions of relatively small and spin-prohibited regions - in relatively

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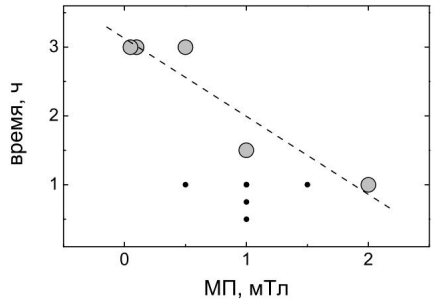


Fig. 3.16: MP intensity and exposure time, which: cause MBE p< 0.05 in tissue brain - O; do not cause the effect - •, according to data [515].

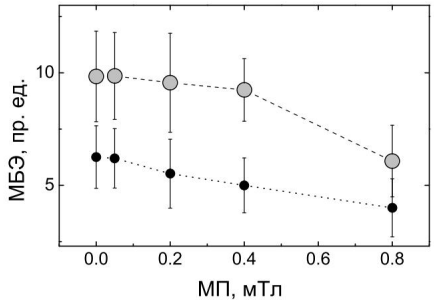


Fig. 3.17: Index of intercellular communication processes in a culture of Chinese hamster lung cells, with and without the carcinogenic drug TPA, according to data [394].

large MP.

Lee, Chang et al. [394] determined whether 50 Hz MF could be a promoter of the carcinogenic action of 12-O-tetradecanoylphorbol-13-acetate (TPA). The characteristics of intercellular communication processes were measured by dye injection followed by counting of the stained cells. Figure 3.17 shows that in these experiments, the MP caused qualitatively the same changes in the biological system as

and a carcinogenic drug. The effect of the drug itself was enhanced in under magnetic field exposure conditions. The range of effective magnetic fields was, as above, in the region of 1 mT.

For all the above experiments recording the biological effects of variable and constant MF, a range from fractions to several mT is characteristic with a monotonic increase in the effect with increasing MF intensity. The RP mechanism of magnetoreception is not involved here.
excluded.

■ Special studies that reliably prove engagement reactions involving RP in magnetoreception are currently unknown. The rate of geminal recombination depends on many parameters:

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viscosity of the medium, the structure and size of the radicals, their g-factors, spins and isotopic composition of the core nuclei, the magnitude and characteristics of the external magnetic field. Various combinations of possible values of these parameters form a variety of physicochemical regimes for the occurrence of radical reactions. This creates difficulties in identifying RPs – possible targets of weak MF. Such studies could, on

At first glance, it seems to be based on the lack of frequency selectivity of the effect. But a complex metabolic system is capable of exhibiting its own characteristic frequencies. This does not allow us to judge the primary mechanism of magnetoreception. By increasing the frequency, sooner or later one can go beyond the relatively low frequency range of the associated chemical-kinetic system. However, here the possibilities become probable thermal and electrochemical effects. Amplitude spectra carry virtually no information, since they are not well defined for either RP reactions or the metabolic system, and depend on

many uncontrollable factors. Probably the only possibility of identifying RP reactions as magnetic field targets could consist of replacing potentially responsible magnetic nuclei with their non-magnetic isotopes.

3.12 The problem of CT in magnetobiology

Today there is no physically acceptable understanding of how Weak low-frequency magnetic fields cause reactions in living systems. Paradoxically, such fields are capable of changing the rate of biochemical processes. reactions, and by resonance type. The physical nature of this phenomenon is unclear, and this constitutes one of the most important, if not the main, problem of magnetobiology.

Many physicists who are not specifically studying this problem ask themselves a question that has become almost rhetorical. The question, although imperfect in form, but correctly focusing attention.
A single act of chemical transformation of molecules requires an initiating impulse with an energy of the order of chem, that is, of the thermal scale.
How then can a quantum of energy of a low-frequency magnetic field, the energy of which is ten orders of magnitude lower, influence this process? Another form of this question appeals to the fact that the act of chemical transformation with characteristic energy ÿT is localized in a microscopic volume.
The same energy of a weak magnetic field H, of the order of ÿT, for example geomagnetic, is contained in a volume V that is twelve orders of magnitude larger (corresponding to the volume of a biological cell). This is easily found from the formula for

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energy density of the magnetic field

$$\ddot{y}T\ddot{y}\ 8\ddot{y}\ \frac{1}{\quad}\ H2\ dV.$$

How can we collect energy in a macroscopic volume and transfer it?
at the micro level? It is widely believed that these issues
as if they close the problem by pointing out the impossibility of MBE. At the same time
There are also counterarguments to this point of view.

Firstly, non-thermally activated reactions are known, for example, enzymatic ones of the "key-lock" type.

Secondly, the very concept of an EMF quantum in the low-frequency range has limited meaning. At a given MP intensity, adequate
The physical description of the EMF is given by Maxwell's classical equations electrodynamics (see 1.4.2).

Thirdly, the concepts of equilibrium are not applicable to living systems. thermodynamics, in particular the thermal scale ÿT In a thermodynamically equilibrium system, the energy ÿT is the average energy of the thermal
motion by one dynamic variable or, as they say, by one degree of freedom. In a nonequilibrium system, in general, there are no objects that could be characterized by energy

ÿT . On the one hand, the thermodynamic factor ÿT must be taken into account.
On the other hand, it is clear that we are dealing with an intermediate region,
where, as indicated in [170], the laws of mechanics and principles of thermodynamics
"... lose their constructiveness, that is, the ability to describe phenomena and predict them."

Fourthly, the two forms of the above question, comparing the energies ÿT in one case the field quantum, and in the other the field energy density, highlight separate aspects, in the first case the frequency,
In the second, it's amplitude, a single, integral essence of the electromagnetic field. This indicates the logical inadequacy of the question.

There are probably other counterarguments as well. What is important, however, is that They have not yet led - and the countdown has already gone on for decades - to the construction of a suitable physical mechanism for magnetoreception.

The issue under discussion contains, in essence, two equally paradoxical questions, and the problem of the biological action of low-frequency magnetic fields has two visible aspects: 1) what is *the mechanism for converting* the signal of a weak low-frequency magnetic field into changes at the level
(bio)chemical process of chem scale and 2) what is *the mechanism for maintaining efficiency,* that is, how such small impacts
are not lost against the background of thermal disturbances of the environment with a scale of ÿT?

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The "kT problem" formulated in this form allows for a detailed physical analysis.

The second question is constructive if the mechanism of transformation is known or proposed. The answer is only to the first question, about the mechanism transformation, does not solve the problem, although it is an integral part of the solution. At the same time, it is apparently impossible to solve the problem without resorting to its analysis, that is, without solving it piecemeal. There are currently no models, that is, systems of equations, that take into account the magnetic and thermal factors together and having solutions that are adequate to experience.

Against the background of the practical completeness of dynamic and statistical theories, the existence of a problem that has not found a solution for several decades, looks strange and provocative. Therefore Many researchers, in the absence of a single theoretical explanation, believe that the experience of electromagnetobiology is an artifact. The proposed transformation mechanisms often encounter objections due to the fact that they do not resolve the second of the above issues, that is, they do not solve the problem as a whole.

As already mentioned, the explanation of the paradoxical action of the weak EMF against the background of thermal noise is often associated with EMF coherence and with the possibility of accumulating its energy by oscillators.

In the case of the microwave range of the electromagnetic field, when the energy the field quantum is only two to three orders of magnitude , the idea of energy storage lower than ÿT, the theory is quite well-founded. However, it is completely unsuitable for explanations of the biological effects of ultra-low-intensity microwave fields discovered by Aarholt, Jaberansari et al. [587], Grundler and Kaiser [568], and Belyaev et al. [428, 635]. The flow of EM radiation here it seems to be absent, but the effect is still observed. The effect is maintained when the radiation power is attenuated from normal to ultra-low, within the range of 10ÿ3–10ÿ18 W/cm2, Fig. 3.1. The effect is controlled by the same mechanism, and this mechanism is not associated with the accumulation of energy, since in the case of ultra-weak radiation there is simply nothing accumulate. This is probably a special problem of a more general nature, which will not be resolved for a long time.

When applied to the low-frequency MF range, the idea of accumulation The energy shortage is hopeless. It takes several years to pump energy MP of the ÿT level, for example, in an ion oscillator, even under ideal conditions, in particular, with an infinite quality factor of the oscillator.

Thus, the distinction between the coherent effect of MF and incoherent noise is in itself insufficient and does not increase understanding

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mechanisms of action of weak magnetic fields. Probably, it would be necessary to somehow take into account the qualitative differences between a magnetic field and thermal effects, its peculiarity as a physical entity. The need taking into account the signal, rather than energy, properties of EMF to explain Its biological action was pointed out by Presman [163] back in 1968.

The peculiarity of the MP is manifested primarily in how the magnetic field is included in the equations of dynamics. Quantities reflecting the action MP and thermal noise have a qualitatively different effect on the behavior of dynamic variables. Naturally, therefore, it is with this circumstance to connect the quantitative energetic incomparability of initiating moments of different nature, magnetic and thermal, leading to responses of similar magnitude. That is, the response to the question must be sought at the level of the primary process of magnetoreception, described by the dynamic equations of microparticles in the magnetic field. It is clear that the ideas of nonequilibrium, instability, etc. recede into the background and, most likely, are a necessary link in the subsequent a long chain from the primary (biophysical) act of MP reception to biological response observed in the experiment.

The second question, which is usually not raised when discussing the informational nature of weak electromagnetic fields, is where and in what the form stores the information that comes from the MP at the very first stages? Only in the case of a constructive answer could the idea of the informational nature of the MP be recognized. Apparently, the only way to preserve information about the MP is to transform it into a state of microparticle(s) in a suitable biophysical system, unless, of course, such storage does not contradict any other principles. An alternative to this assertion is not yet visible.

Thus, these considerations converge on all sides on the need to study the dynamics of microparticles in the magnetic field. This topic looks has been studied for a long time and is well-studied. It turns out, however, that quantum dynamics of sufficiently heavy particles such as ions, combined with nonlinear properties of biophysical systems lead to a number of features in the dynamics of such systems. They can successfully explain biological action of weak low-frequency magnetic fields.

According to one of the general principles of quantum physics, measurement the energy of a quantum system cannot be determined with an accuracy of ÿ faster than the time /ÿ. In particular, any observation of the consequences of the absorption of a photon with energy ÿ = ÿ by a quantum system will require at least a time of 1/ÿ. The low-frequency range of fields, used in more or less well reproducible magnetobio-

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logical experiments, starts at approximately 10 Hz. Therefore, the necessary conditions for measurement must be maintained for at least
0.1 c. In particular, the lifetimes of the states of a quantum system absorbing a photon must be of the same order of magnitude or greater.

Such long-lived states at T ÿ 300K may appear
implausible. However, if the experiment shows that the MP
This frequency range still causes effects, then the assumption of the presence of long-lived modes seems justified. This is not exotic. For example, the spin states of protons in liquid water
at room temperature they "live" for about 3 C. Moreover, as the temperature rises, the lifespan also increases, contrary to expectations. This is a consequence features of the interaction of water proton spins with thermal disturbances.

Spin relaxation is controlled by the relativistic spin-orbit relationship
interaction proportional to the gradient of the microscopic
electric field. Due to the high diffusion mobility
proton, increasing with increasing temperature, the microrelief of the electric
the field is largely averaged and smoothed for the proton. Therefore
the proton “sees” the electric field as very uniform and almost
interacts with it. This was said in relation to the spin-lattice
relaxation. Spin-spin relaxation is caused by magnetic
dipole-dipole interaction of protons with each other. The average magnetic field on a proton from the side of magnetic moments
other protons are relatively few and spin-spin relaxation is also
difficult. This does not mean that the spin states of protons in general
do not appear. As will be shown in the relevant sections, accounting
states of nuclear spins of protons and ions leads to important
magnetobiology consequences.

The relatively long lifetime of spin states is due to the peculiarities of the interaction of spins with thermal vibrations.
lattices. Similarly, the metastability of some spatial
or, as they say, orbital or non-spin, degrees of freedom can be determined *by the peculiarities* of their interaction with thermal
fluctuations.

It is known that energy transport along protein ÿ-helical polymer molecules can be explained by the soliton transfer of vibrational energy of C=O atoms in the peptide groups of protein monomers.
chains [72], see Appendix 6.6. Indirect experimental evidence for the existence of solitons in proteins was obtained from the spectrum
absorption of crystalline acetanilide, chains of hydrogen bonds

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which are analogous to the bonds of peptide groups in ÿ-helical proteins [671]. The use of the Davydov soliton concept in biophysics is associated with its possible stability at physiological temperatures of ÿ 300 K. Davydov [73] analytically examined the thermal effects and showed that a soliton exists at physiological temperatures. Kadantsev, Lupichev, and Savin in their work [99], Cruzeiro, Halding, and

[692] studied numerically the dynamics of a soliton with quantum considerations thermal vibrations and showed that thermal vibrations contribute to the formation of a soliton. On the contrary, Lomdahl and Kerr in [538], Lawrence, McDaniel et al. [382] showed that taking into account thermal vibrations in numerical modeling based on the "classical" Langevin equation reveals instability of the Davydov soliton near physiological temperatures. To date, the question of the stability of the Davydov soliton in protein macromolecules under conditions of thermal vibrations remains open. At the same time, it is clear that the existence of long-lived excitations of orbital degrees of freedom at room

temperature is at least not prohibited, see, for example, the work of Zolotaryuk, Pnevmatikos and Savin [736].

When discussing the “kT problem”, one must also remember that the concept itself ÿT comes from statistical physics. It only makes sense for systems in a state not too far from statistical equilibrium. Indeed, in such systems, the quantum ÿ does not noticeably change the average statistical energy of one degree of freedom of the dynamic system. But in systems far from equilibrium, for example, in systems weakly coupled to a thermostat, when the thermalization process

comparatively slow, a field quantum causes a large relative change in the energy of some degrees of freedom. It is well known that the metabolism of living systems is a set of predominantly nonequilibrium processes. The emergence and decay of biophysical structures, occurring on time intervals shorter than the thermalization time of the degrees of freedom of these structures, provide a good example of systems far from equilibrium, where even weak field quanta are not prohibited manifest itself in the parameters of structure decay. In other words, if the lifetime (thermalization) of some degrees of freedom interacting with field quanta is greater than the characteristic lifetime of the field itself systems, then such degrees of freedom are in the absence of temperatures as such and a comparison of changes in their energy with ÿT at absorption of field quanta loses its meaning.

The mechanism of interference of quantum states of an ion in an idealized protein cavity, proposed by the author in [22, 293], is reduced to

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to the next one. The ion enters the protein cavity through relatively narrow "gate" and resides there in a superposition of quantum states, the eigenfunctions of the Hamiltonian. The ion probability density contains an interference contribution, which makes its distribution in the cavity non-uniform. In a constant magnetic field, the distribution pattern rotates around the direction of the magnetic field as a whole with the cyclotron frequency. It turns out that by imposing an additional variable magnetic field with special parameters, you can kind of stop the rotation pattern. A long period of stop or very slow rotation is followed by a rapid turn. The pattern seems to freeze,
This is similar to the movement of the frame-changing clamshell mechanism in first-generation movie projectors. In this state, the tunneling rate of an ion from a protein is a nonlinear function of the probability density. ion near the gate changes noticeably. Formulas relating "magnetic" part of the probability of dissociation of the ion-protein complex with the parameters of the magnetic field. The formula predicts polyextreme spectra in terms of frequency and amplitude of the magnetic field.

Metastability of the angular modes of ionic oscillations, or more precisely, metastability of the phase difference of Zeeman sublevels in this mechanism, is postulated. Note that it is not a new entity that is postulated, but a certain property of an already known object. The rationale for this is formulas derived for a number of magnetobiological effects, which, on the one hand, have predictive power, and on the other, are in good, and in some cases surprising, agreement
with experimental data from different authors. That is, the requirements scientific methodology are met. Good agreement indicates that the interference mechanism of converting the MP signal into a biochemical response is quite real and it makes sense to investigate the reasons for it performance under conditions of thermal disturbances of the protein walls capsules.

Section 5.4 discusses the molecular gyroscopic degree freedom, which apparently has a relatively long lifetime. Combined with interference effects, such a model allows for the interpretation of the MBE without resorting to serious
postulates, and thus claims to solve the “kT problem”.

3.12.1 Interference in a magnetic field

Let us illustrate the interference mechanism of the MBE in the following thought experiment with the interference of microparticle waves. Charged particles from a source can pass through two slits and form

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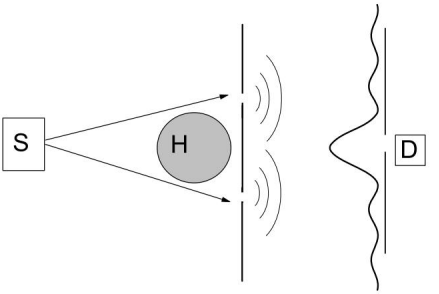


Fig. 3.18: Interference of charged particles in an alternating magnetic field: S is the source of particles, H is the magnetic field perpendicular to the plane of the figure, D is the particle detector.

thus create an interference pattern on the screen, Fig. 3.18.
In the center of the screen there is a small hole behind which a target, a particle counter, is installed. The alternating magnetic field H(t) = H sin ÿt induces a circular electric field that shifts the phases of the wave
fields in opposite directions. As a result, the interference pattern oscillates relative to the position corresponding to
H = 0, with the frequency of the magnetic field.

The characteristic natural frequency here is obviously that
a combination of particle and MP parameters that has the necessary
physical dimension, that is, ÿc = qH/M c. Therefore, when varying the magnetic field, the particles will arrive at the target with a phase difference of the order of ÿ ÿ (q/M c) H(t) dt or

$$\ddot{y}\,\ddot{y} \quad \frac{\ddot{y}c}{\ddot{y}} \sin \ddot{y}t.$$

It is easy to see that the interference pattern will either be stationary,
in the case of high frequencies of the external MP, or completely blurred, in
in the case of low frequencies. Obviously, the most significant changes occur in the frequency range corresponding to the cyclotron frequency of particles, although, of course, no cyclotron resonance can be assumed.
there will be no talk.

Note that the interference intensity, like other observable quantum quantities, oscillates with increasing phase. Consequently, sine-on-sine dependences appear here, which

are conveniently represented as series of Bessel functions. Therefore, the dependences of the observed quantities on the amplitude of the magnetic field in the manner of Bessel functions functions are a characteristic feature of magnetic effects involving oscillating phase differences.

As follows from the last relation, the amplitude of oscillations of the interference pattern will change with variation of both the frequency

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both the frequency and the amplitude of the magnetic field. If they are selected so that at the extremes positions of the pattern, the counter will have interference maxima, the counter will register the maximum particle flux. In
in the general case, the dependence of the particle flux on any of the parameters The MP will have a polyextreme character.

In relation to this interference scheme, it would also be possible raise the question: why is a weak MF, the energy quantum of which is many orders of magnitude less than the characteristic energy of the processes in a particle counter, does it nevertheless cause significant changes in the intensity of the particle flux? The answer can be seen from Fig. 3.18 and obviously does not constitute
paradox. Interference phenomena based on phase shifts utilize essentially classical properties of the electromagnetic field. In the quantum description, as suggested by the form of the question, interference phenomena correspond to multiquantum processes. It follows that the "kT problem" in its original form

the formulation that assumes a single-quantum process is incorrect delivered.

■ The condition for the observability of interference assumes the proportionality of the characteristic length of the problem R and the de Broglie wavelength of the particles ÿB = 2ÿ/p. It follows that the magnetic field-dependent interference of ions could be observed on microscales: the wavelength of the
Broglie for biologically important ions at physiological temperature is tenths of A
^{o}. The cavities of some proteins that bind ions are designed in such a way that they seem to implement an interference scheme in a magnetic field at the micro level.

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Chapter 4

Interference
bound ions

Interference or mutual amplification and cancellation of waves is a common property of wave systems of different nature: elastic, electromagnetic, etc., for which the principle of superposition is valid. According to
According to the superposition principle, the complex amplitude of the resulting wave is equal to the sum of the amplitudes Ai of the component waves: A = Ai. If the observed parameter is a nonlinear function of amplitude, for example,
intensity, that is, the square of the amplitude modulus, then interference will be manifested in the distribution of this parameter. Intensity
the resulting wave at any point

$$|A|^2 = \sum_i |A_i|^2 + \sum_{i=j} A_i A_j$$

as can be seen, it differs from the sum of the intensities of the component waves, in which is what amplification or damping of waves consists of.

According to L. de Broglie's hypothesis (1924) on the universality of wave-corpuscular duality, wave properties are exhibited by any particles of matter, and not only by photons—quanta of the electromagnetic field. Moreover, the characteristic wavelength λ_B corresponding to a particle with
momentum p is equal to $\lambda_B = 2\pi\hbar/p$. The obvious criterion of observability
interference is that the de Broglie wavelength must be comparable to the scale r of the observation system. This is a significant limitation that does not allow one to observe, in particular, interference of the maximum

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roscopical particles. At the same time, interference is well known
electrons, atoms and even molecules.

The interpretation of the nature of de Broglie waves proposed by M. Born is connected with the quantum-mechanical description of particles using the wave function or complex probability amplitude ÿ. The quantum state of a particle is generally described by a superposition of its possible
states

$$ÿ(x)= \sum_i aiÿi(x) ,$$

where ai are complex coefficients, x is a set of variables. The probability density of detecting a particle at a point x0, according to M. Born's concept, is equal to

$$|ÿ(x0)|^2 =ÿÿ(x0)ÿ(x0)= \sum_i |ai|\,2|ÿi(x0)|\,2 + \sum_{i=j} aÿajÿÿ\, i\,(x0)ÿj\,(x0) ,$$

which also contains an interference (second) term.

The main way to observe interference is to create
conditions for diffraction (scattering) of free particles on regular
structures with a period of the order of the de Broglie wavelength of these particles.

Diffraction of photons in the optical range is observed on optical diffraction gratings with a period of ÿ 10ÿ4 cm. The energy of X-ray photons is several orders of magnitude greater; gratings formed by the regular structure of matter, mainly crystals, are suitable here.

Observe the interference of particles that also have rest mass.
Electron diffraction by surface irregularities is the basis
various electron microscopes. The energies of heavier particles, protons, neutrons, and light atoms can be selected (created) in such a way that their de Broglie waves fall within the range

^{o} = 10ÿ8 cm. In this case, the scattering of particles on regular structures is
In tours of this scale, that is, in crystalline bodies, it creates diffraction maxima of the particle flux in certain directions, which can be found from the condition of constructive interference of particles.
In this case, the transformation of information about the microscopic occurs.
spatial structure of scattering crystals in the angular distribution of maxima, easily recorded in an experiment at the macro level.
Interference occurs here in the flow of free particles probing the microstructure of the substance.

Interference of waves or quantum states of helium atoms at
diffraction on a grating formed by a standing EM wave, i.e., photons, was investigated in [540].

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Interference of bound particles is also possible. The principle Heisenberg's uncertainty theory (1927) states that for a particle localized in a microscopic region of space of size r,
the average value of the impulse will be no less than ÿ /r, respectively, de Broglie wavelength ÿB < , 2ÿr. Then, according to the criterion of observability of interference, observation is possible if the measurement of the particle's state is localized in the same region of r. Interference of bound electrons is observed. This is known as interference.
quantum atomic states, see, for example, the monograph by Aleksandrov, Khvostenko and Chaika [7], although, in essence, the nature of the interference of free particles is also quantum. Interfering states
electrons in an atom are probed using electromagnetic radiation in the optical range, the wavelength of which is 4 orders of magnitude greater
atomic distances. This range of EMF corresponds to the energy of quantum transitions between interfering states, on the order of fractions of an eV, and is therefore the most suitable. Radiative transitions induced by an optical field, in the simplest example,

from two adjacent levels to any lower level, are accompanied by the emission of electromagnetic waves with close frequencies.
The interference of these waves leads to the experimentally observed modulation of the radiation intensity with a difference frequency. In this sense, it is not It is entirely correct to speak about the interference of atomic states, although the term has long been accepted in the literature.

Scattered light, including modulated re-emitted
waves, carries information about the intra-atomic state of electrons, which allows for a deeper understanding of the structure of matter.

On the interference of bound particles - not electrons, for example ions, has not been previously reported.1 This is due to some features observations of interference of atomic states.

It is also legitimate to speak of the interference of atomic states in the precise sense, without regard to the interference of re-emitted probe light. More generally, we can speak of the interference of bound states such as atomic states. Let us illustrate this with the following example.

Let us assume that there is some instrument that allows us to measure the probability density distribution of a particle bound in an arbitrary central potential, in the area of its presence. Let the measured quantity is the angular distribution of the density p(ÿ). If the particle is in the p-state, then the orbital and magnetic quantum numbers

1except for some phenomena in high-energy nuclear physics

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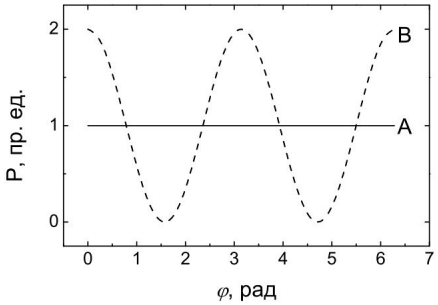


Fig. 4.1: Angular distribution probability density: A — in the state m = 1, B — in the superposition of states m = ±1.

la are equal to l = 1, m = 0, ±1. The angular mode of the wave function in the state m =1 is equal to 2 eiÿ, therefore the angular distribution of the density is uniform, p(ÿ)= |eiÿ|2=1, Fig. 4.1-A. The same is true for a particle in the state m = ÿ1. If there is a superposition of states m =1 and m = ÿ1, then the probability density depends non-trivially on the angle, for example:

$$p(ÿ)= \left| \frac{1}{ÿ2} eiÿ + \frac{1}{ÿ2} eÿiÿ \right|^2 = 2\cos 2 ÿ.$$

That is, the particle is predominantly located in certain angular sectors of the area of stay, around the values ÿ = 0 and ÿ = ÿ, Fig. 4.1-B. Polarization occurs, or more precisely, the alignment of the particle's state along some axis.

The wave functions of a particle also have phase factors that depend on the energy of the state and on time eÿiÿt/. For states m = ±1 energies are the same and the presence of additional phase factors does not change the situation. Changes occur in the magnetic field H. In this case, it is necessary to take into account the Zeeman splitting of the initially degenerate states m = ±1, whose energies are now equal to ÿ± = ÿ ±ÿ. Then for the probability density we obtain

$$p(ÿ)= \left| \frac{1}{ÿ2} eiÿeÿiÿ+t/ + \frac{1}{ÿ2} eÿiÿeÿiÿÿt/ \right|^2 = 2\cos 2 ÿ\, ÿ \quad \frac{ÿ}{} t \quad .$$

In a coordinate system rotating around the z-axis H with an angular velocity ÿÿ/, the angular distribution is obviously stationary. Therefore, in In a laboratory system, the sectors where particles are predominantly located rotate with an angular velocity ÿ = ÿ/. And if the measuring instrument has an inertia that does not allow it to register

2Here, irrelevant normalization coefficients are omitted.

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If any changes occur faster than in ÿÿ1 time , then measuring the angular distribution becomes impossible. The meter will show uniform distribution. It turns out, however, that by imposing on By introducing an additional variable magnetic field of a certain frequency and amplitude into the system, it is possible to effectively stop the rotation of the sectors (see section 4.1.1). In this mode, the registration of the sector structure of the wave functions become possible again.

Thus, there are several modes of magnetic resonance that allow one to observe the interference of bound quantum states. This is the zero MP (magnetic vacuum) and a number of combinations of constant and alternating MP with certain parameters. The latter, as will be clarified below, depend on the level of constant magnetic field and the properties of the bound particle.

What device or method would be suitable for registering a sector? structure of the wave function of a bound particle in an MF? In the case of electronic states in atomic spectroscopy, the polarization of an atomic state can be judged by the polarization state of the re-radiated electromagnetic field. Is it possible to record polarization outside

means of probing radiation? Probably the most obvious way would be to arrange a local reduction in the potential in a small angular region of the total solid angle. Let a particle be enclosed in an impenetrable sphere with a hole, and at the hole the particle's potential is reduced to some finite value. The particle overcomes the potential barrier by tunneling. Since the probability of a tunnel transition depends on the probability density of the particle's presence near the "hole," the decay of the bound state, the exit

particles from the area of its metastable presence could serve indicator of special MP conditions leading to the emergence of a sectoral structure.

One interesting variant of this scheme is associated with a recently discovered and intensively studied class of structural organization carbon atoms - fullerenes [331, 259, 691]. The molecular formula of these compounds is C60, C70 , etc. The peculiarity is that the fullerene molecule has the shape of a spherical shell, or more precisely, the shape high-order polyhedron. The cavity of the fullerene may also contain "foreign" atoms, which over time, due to quantum diffusion, leave the shell. A short review of such so-called endohedral fullerenes as Ca@C60, Y@C82, La@C82 , etc. is presented in [257] It is logical to assume the presence of effects of weak MP, the influence fields on the decay rate of the metastable bound state of endofullerenes. In [619], the internal cavity of fullerenes containing

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The 3He atom was probed using NMR spectroscopy. The influence of magnetic field variables on processes involving endofullerenes is unknown.

Another potential way to independently observe this is

The effect lies in the field of tunneling microscopy. Using scanning tunneling microscopes, two-dimensional electron states arising on the surface of copper, silver, gold, etc. have long been studied, see, for example, [256]. The images clearly show

patterns of surface electron density arising due to
interference of electron waves incident and scattered by surface defects [360]. The following are proposed as surface defects:
adsorbate molecules that can be, using scanning
microscope needles are organized in the form of an arbitrary shaped container for electrons [732]. Thus, the authors [359] managed to place on
An atomically smooth copper surface of 48 iron atoms in the shape of a closed circle. Characteristic density waves formed within it, like those on the surface of water after a thrown stone. Electrons trapped in a suitable container find themselves in a metastable state. The superposition of angular modes of such a bound state in
A properly selected magnetic field will produce an interference redistribution of electron density. Naturally, one could attempt to detect it with the same microscope. A reader inclined to generalize would see here a prototype of magnetically controlled *nanoscopic* memory cells for future computers.

Suitable cavities are probably also present in some crystalline salts of the electride type , in which the cation is ionically bonded to crown ethers [411].

An interesting object for possible observation of interference effects of dissociation are crystals, polycrystals and solutions of trimethylsilite derivative of silicate anion. The molecule of this substance [(CH3)3) Si]8Si8O20 is distinguished by the fact that it forms in the center
a nearly cubic cavity of 20 oxygen atoms. The oxygen atoms are located at the vertices and at the centers of the edges of a cube deformed to a sphere. Such a cavity, as shown in [673], is capable of holding hydrogen atoms without forming a chemical bond with them. Bombardment with ÿ-rays of radioactive 60Co knocks out methyl groups
part (4.3 10ÿ5) of hydrogen atoms that end up inside the cavities. Atomic hydrogen was identified by the g-factor and hyperfine splitting of the EPR doublet. Remarkably, the EPR spectra of atomic hydrogen could be observed for several years if the samples were not heated above 150 o C. Experiments with such a substance

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are particularly convenient because hydrogen tunneling from cavities
is directly related to the intensity of the EPR signal.

Of most interest are the cavities of protein macromolecules that bind certain ions. Since protein activity, including in relation to other enzymes, depends on the presence of an ion in a bound state, the effect of magnetic fields on the probability of dissociation of the bound state,
dissociation of the ion-protein complex could lead to biological effects. Interestingly, the data from magnetobiology experiments do not contradict this hypothesis [293, 297, 296, 300, 303].

■ For most biologically significant ions, the wavelength
de Broglie, even at T = 300 K, is only three to six times less
their ionic radii and is close to the dimensions of the effective potential
binding cavity. For example, the ion-ligand distance in the calcium-binding site of the protein troponin C is 2.4 A [627]. This site also
binds magnesium ions. The ionic bond radii of Ca2+ and Mg2+ are equal, respectively, ny 1.74 A and 1.36 Å so that the effective radius
potential is 0.7–1 A · At the same time, their de Broglie wavelengths
ÿ = 2ÿ/p equals 0.28 A and 0.36 Å at an average thermal impulse
p = ÿ 2MkT. Thus, at the atomic scale, ions exhibit
properties that cannot be reduced to the behavior of classical particles. Quantum mechanics proves necessary to describe ionic states within protein cavities.

4.1 Dissociation of ion-protein complexes in

magnetic field

This section describes a physically consistent model that explains one of the mechanisms of action of weak low-frequency
magnetic fields on biological systems. The process of changing the probability density of an ion inside a protein in a magnetic field is considered,
modulated in magnitude. It has been shown that the probability of dissociation
The ion-protein complex significantly depends on the magnetic field parameters, which is a consequence of the interference of angular modes of the ion's quantum states inside the protein cavity. Frequency-amplitude dependences for the ion binding probability, or more precisely,
the probability of dissociation of the ion-protein complex, based on a consistent physical model.

Protein ion binding reaction

protein(..)+ I protein(I)

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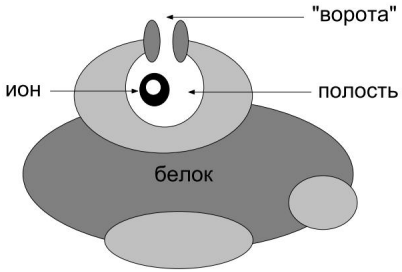


Fig. 4.2: Ion enters the bond
calling cavity through the gates formed by
the internodes
oxygen-binding ly-
Gandov.

is as follows. The protein sort of captures the ion into the cavity,
formed by ligands. In this state, biological activity
protein is altered. Since MP is capable of shifting the equilibrium of this reaction, the change in activity ultimately manifests itself at the level
measurable biological response.

The ion enters the binding cavity through the “gate”, Fig. 4.2.
He finds himself trapped in a cavity because the potential barrier
the collar is quite high. According to experimental data of biochemical
The kinetics of the relaxation time of the equilibrium of this reaction is of the order of 0.1 s, see p. 285. The assumption on which the following model is built is that the probability of ion release is not indifferent to the quantum state of the ion in the cavity. We will assume that the probability of ion release or dissociation of the ion-protein complex depends nonlinearly on
probability density of the ion near the gate. Due to the interference effect of the quantum states of the ion, the magnetic field causes a redistribution
ion cloud, which affects the equilibrium constant of the reaction.

The structure of some calcium-binding proteins is known with an accuracy that allows us to form an idea of the internal geometry of the ion-binding cavities. The work [627] reports the results of a diffractometric analysis of the structure of the protein troponin C.
The use of a synchrotron radiation source determined the high- Troponin C binds some resolution, about 2 A° 4 Ca2+ ions with two
cavities with high affinity for calcium, which also bind
Mg2+ ions , and two with low calcium binding by troponin C
entails a significant conformational rearrangement of the protein, which is ultimately transmitted to the level of the observed biochemical or
biological response. The coordination of calcium ions in the cavities approaches seven. The structure of the high-affinity cavities is shown in Fig. 4.3. The arrangement of the ligands is close to octahedral with a distance between the ligands R ÿ 2.4 A° · Ionic radii of calcium atoms

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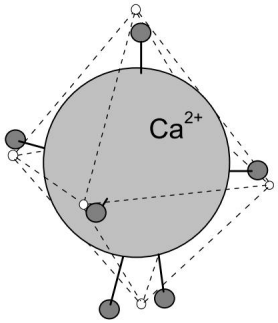


Fig. 4.3: Octahedral coordination of an ion in a bonding protein cavity, preserved proportions of ionic radii particles and ligands and size cavities. According to data [258, 627].

tion and oxygen of the ligands are equal to 1.74 Å and 0.136 ÅResults practically similar to those indicated were obtained in [258] for the binding cavity of the protein calmodulin.

As can be seen from Fig. 4.3, the size of the motion region for the calcium ion is is quite small. This makes the potential of the calcium ion inside the cavity very close to a spherically symmetric or central potential. For an approximate numerical estimate, we assume that the ions form rigid spheres of the corresponding radii, the ligands are fixed in
their idealized octahedral positions, and the displacement of the central ion is limited only by the contact of the ionic spheres. Let,
For example, an ion is displaced in a horizontal plane. The smallest displacement is in the direction of the ligand. The largest is in
direction between the ligands. The dependence of the maximum possible displacement x, from the polar angle follows from geometric considerations

$$x(ÿ)= r \cos ÿ \; ÿ \; (rca + rox)2 \; ÿ \; r2 \sin2 ÿ, \; 0 \; ÿ \; ÿ \; ÿ \; ÿ/4 \; ,$$

where r is the distance from the center of the cavity to the center of the ligand, rca and rox are ionic radii of calcium and oxygen atoms. From this function, one can
isolate the constant component, which is related to the central potential, and the angle-dependent part, which represents an additional potential function with low-order symmetry. Omitting the calculations, we will only point out that for the given ion sizes

and cavities, the potential function is approximately 80% composed of centrally symmetric potential of radius 0.7 A , which is a little more Bohr radius of the electron. Therefore, in the mathematical model, we will consider the ion as a point charge in the effective potential of radius about 0.7 A .

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4.1.1 Model

Let us accept the idealization that an ion is a particle with a charge
q and mass M, which in general has its own angular
I, in units of and nuclear magnetic ÿ moments. The ion is
in the spherically symmetric potential U(r) created by the walls
protein binding site. The ion enters the binding site through a relatively narrow "gate," the clearance of which depends on the probability density of the ion near the gate.

The Hamiltonian of a free particle in the MF can be found in many books, for example [664, 122] and others. With an accuracy of up to terms ÿ cÿ1 it is written in the following form

$$H = \frac{(P \ddot{y} \bar{q} cA)2}{2M} + qA0 \ddot{y} \ddot{y}I H .$$

Here P = ÿiÿ is the momentum operator, A, A0 are the vector and scalar potentials of the electromagnetic field, H = ÿ×A is the intensity
MP is Planck's constant, ÿ = ÿ/I is the gyromagnetic ratio.
Let us choose the potentials of the external homogeneous field in the form A = H × r/2, A0 = 0. Then, for a spherically symmetric potential U we write

$$H = \frac{P^2}{2M} + U \ddot{y} (bL + \ddot{y}I) H + \frac{q2}{8Mc2} (H \times r)^2 . \qquad (4.1)$$

Here L = ÿir ×ÿ, I are the operators of angular and spin momenta,
b = q/2Mc is the ion parameter. It is taken into account that

$$A\ddot{y} = \ddot{y}A = 2 \quad \frac{1}{} \ddot{y}(H \times r) = \quad -\frac{1}{2} H(\ddot{y} \times r) , i A\ddot{y} = \ddot{y} H \frac{q}{Mc} \quad \frac{q}{2Mc}$$

We neglect the contribution ÿ A2 (see, for example, estimate (5.28)), that is, the last term of the Hamiltonian, which determines the small diamagnetic susceptibility of the system. Then Hamiltonian (4.1) includes
kinetic, potential, and Zeeman (orbital and spin) energies. For ions with nuclear spin, the coefficients
in (4.1) satisfy the inequality ÿ>b. Therefore, one cannot neglect
spin effects, they are discussed in sections 3.10 and 4.8, here
we assume I = 0. If the magnetic field changes only in magnitude, but not in direction, then

$$Hx = Hy = 0 , Hz = HDC + HAC \cos(\ddot{y}t) , \qquad (4.2)$$

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then the projection of the moment onto the z-axis is preserved in the potential U(r).[3] Correspond-
we replace the corresponding operator with its eigenvalues lz = m
and the Hamiltonian takes the form

$$H = H0 \ddot{y} \ddot{y}mHz , \qquad H0 = + U \ddot{y}\ddot{y}m = mb. \quad (4.3)$$

In the absence of magnetic field, the wave functions of the ion (eigenfunctions of H0) have, up to normalization, the form [122]

$$\ddot{y}klm = Rkl(r)P|m|_{l} \quad (\ddot{y}) \exp(im\ddot{y}) , \quad (4.4)$$

where Rkl are radial functions depending on the type of U(r). $P_{l}^{m}(\ddot{y})$ — associated Legendre polynomials, k, l, m — radial, orbital (or azimuthal) and magnetic quantum numbers, r, ÿ, ÿ are spherical coordinates. The operator ÿÿmHz, which is reduced to the multiplication operation, obviously does not act on the functions (4.4) and therefore changes only instantaneous values of the energies of these states (Zeeman splitting). No quantum transitions in the states of the ion under the action of the field (4.2) occur, and accordingly, there are no resonant conditions for transitions. What can depend on the MP parameters in this case?

Let us write down the solution of the Schrödinger equation with Hamiltonian (4.3)

$$\ddot{y} = \sum_{kmm} aklmRkl(r)P|m|_{l} \quad (\ddot{y}) \exp im\ddot{y} \ddot{y} \quad \frac{i}{-}\ddot{y}klt + \frac{i}{-}\ddot{y}m Hzdt , \quad (4.5)$$

where ÿkl are the unperturbed energies of the states ÿklm, and the coefficients aklm sets the initial conditions.

To obtain values that can be compared with experimental data, ensemble averaging will need to be performed below.
independent particles. Therefore, it would be necessary to indicate in (4.5) random phases of angular modes exp(imÿ) defined on the ensemble. Taking into account note that the statistical distributions of these phases are uniform in

3The Zeeman effect, which underlies the considered interference of quantum states in a magnetic field, occurs only in the presence of degeneracy in the directions of the system's angular momentum, which requires at least axial symmetry of the potential. A magnetic field removes the degeneracy by splitting levels with a certain angular momentum value into
sublevels with different values of the moment projection onto the axis of symmetry. These sublevels correspond to the eigenfunctions of the magnetic moment energy operator in the magnetic field. Any operator is diagonal in the representation of its eigenfunctions, therefore, the uniaxial magnetic field in in any case, it does not cause transitions in the states of the Zeeman multiplet.

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interval [0, 2ÿ), the mathematical expectation of the corresponding harmonic processes can be found in the ergodic approximation, as limit of the average over an infinite time interval. This is further adopted the averaging form as simpler to present. Random phases are not are written out, and all formulas obtained by averaging over an infinite time interval should be understood as formulas for averages over ensemble of particles.

Let's find the probability density of finding an ion near the "gate", then there is, for some value ÿ = ÿ0:

$$p(ÿ0,t)= ÿ(ÿ0,t)|ÿ(ÿ0,t)r,ÿ = \sum_{mm} amm \exp imÿ0 + imb \int Hzdt \quad , \tag{4.6}$$

where m denotes the difference between quantum numbers m ÿ m. The coefficients

$$amm = \sum_{k,k',l,l'} aÿ\, klmak'lm \exp \frac{i}{-} (ÿkl ÿ ÿk',l')t\, Rkl|Rk',l' \quad P|m| \; |P|m'| \tag{4.7}$$

are the elements of the density matrix in the representation of the eigenfunctions of the operator lz. They consist of constants (k = k , l = l) and rapidly oscillating terms. Indeed, for a Ca2+ ion in a trap, merom R ÿ 0.7 A° In the ground and first excited states, the frequency of these oscillations is of the order of /MR2, i.e., about 1011 Hz. This size corresponds to the Ca-binding cavity of the protein troponin-C [627]. Calmodulin, a low molecular weight regulatory protein, is widely present in living tissues, has a similar size of binding cavities, [258]. The sizes of various cavities of other proteins are given in [722]. Since averaging over the time interval T 10ÿ10 s will be performed below, the elements amm can be considered constant. Transforming (4.6) taking into account (4.2), we find 4.

$$p(ÿ0,t)= \sum_{mm} amm \exp im\, ÿ0 + ÿ0t + \frac{ÿ1}{ÿ} \sin(ÿt) , \tag{4.8}$$

$$ÿ0 = bHDC ,ÿ1 = bHAC ,b = q/2Mc.$$

The frequency ÿ0 = qHDC/2Mc is called the Larmor frequency. Note that that the quantity in parentheses in (4.8) is proportional to the phase difference interfering angular modes.

4To switch to the MKS system of units, we must assume b = q/2M

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It can be shown that on average over time p = Const. First, we write down the average of p over a finite time interval [ÿT,T], which
will be needed in the future

$$pT\ \ddot{y}\ \frac{1}{2T}\int_{t\ddot{y}T}^{t+T} p(\ddot{y}0,t)\,dt = \qquad (4.9)$$

$$= \frac{1}{2\ddot{y}T}\sum_{mm} amm\exp(im\ddot{y}0)\int_{\ddot{y}(t\ddot{y}T)}^{\ddot{y}(t+T)} \exp(i\ddot{y}z\ddot{y})\exp(iz\sin\ddot{y})\,d\ddot{y}\ ,$$

where the notations are introduced

$$z = m\ \frac{\ddot{y}1}{\ddot{y}}\ ,\quad \ddot{y}z = m\ \frac{\ddot{y}0}{\ddot{y}}\ ,\ddot{y} = \frac{\ddot{y}0}{\ddot{y}1} = \frac{HDC}{HAC}\ . \qquad (4.10)$$

Because

$$\exp(iz\sin\ddot{y}) = \sum_{n=\ddot{y}\ddot{y}}^{\ddot{y}} Jn(z)\exp(in\ddot{y})\ , \qquad (4.11)$$

then the integral in (4.9) is easily calculated. It is equal to

$$2\sum_{n} Jn(z)\ \frac{\sin[(\ddot{y}z + n)\ddot{y}T\ ]}{\ddot{y}z + n}\ \exp\ [i(\ddot{y}z + n)\ddot{y}t]\ .$$

After substituting it, (4.9) takes the form

$$pT = \sum_{mm\ ;n} amm\exp\ [im\ddot{y}0 + i(\ddot{y}z + n)\ddot{y}t]\ \frac{\sin[(\ddot{y}z + n)\ddot{y}T\ ]}{(\ddot{y}z + n)\ddot{y}T}\ Jn(z). \qquad (4.12)$$

In the general case, when $\ddot{y}z + n = 0$

$$\overline{p} = \lim_{T\ddot{y}\ddot{y}}\ pT = \sum_{m} amm\ , \qquad (4.13)$$

since all terms of the sum (4.12) with m = m tend to zero. This expression does not depend on the MP and we arrive at a trivial result,
which cannot be linked to the patterns observed in experiment.

In a particular case, the frequency of the external MF can be chosen so that the condition $\ddot{y}z + n = 0$ is satisfied:

$$\ddot{y} = \ddot{y}m\ \frac{}{n}\ddot{y}0\ .$$

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The condition will be satisfied for several members of the sum for which
m, m , n are such that m/n has the same magnitude. These terms create a time-
independent contribution to pT

$$\sum_{mm;n} amm \exp [imÿ0]Jn(z) .$$

That is, under these special conditions, substituting z = ÿn/ÿ, we obtain

$$\overline{p} \ÿ \text{Const1} + \text{Const2} \sum_{n} Jn(ÿn \frac{HAC}{HDC}) . \qquad (4.14)$$

It would seem that the desired behavior of the model system has been found.
some frequencies of the external field, determined by the equality

$$ÿp = \frac{m}{n} ÿ0 \ , \qquad (4.15)$$

a special situation arises when the probability of an ion being in a certain angular position ÿ0
non-trivially depends on the magnitude of the constant and the amplitude of the alternating
magnetic field according to formula (4.14). This
could explain the experiments where MBE is observed in similar magnetic
conditions. However, this explanation is incorrect, since equality
ÿz+n =0 is not physically feasible in the experiment. Any infinitesimal deviation
from it leads to the result p = Const, different from (4.14). The probability density
p, considered as a function
frequency of the MP ÿ is not continuous at the points (4.15)

$$\lim_{ÿ\ÿÿp} \overline{p}(ÿ) = p(ÿ\overline{p}) .$$

Experience shows a different, smooth, dependence of the MBE on frequency. Such
the discrepancy in the explanation could be interpreted as
broadening of the resonance curve due to attenuation. But in this case, as already mentioned,
there is no resonance itself, and the concept of resonance width is meaningless. The
incorrectness is also due to the fact that
the expression for the quantity (4.14), compared with the MBE, depends on the
angle ÿ0, which is obviously not a parameter of the model. It is necessary to
perform averaging, but this will also lead to a trivial result
$\overline{p}$ = Const, which is not related to experience.

The solution is to take into account the nonlinear nature of the relationship
between the probability density p(ÿ0,t) and the intermediate value, the probability
the exit of the ion from the binding cavity, the changes of which in the final
The MBE is called in this regard.

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Let the probability P of the actual biochemical reaction, the dissociation of the ion-protein complex, depend *nonlinearly* on the probability p of the particle being near the "gate." We will limit ourselves to taking into account the linear and quadratic terms of the expansion5

$$P(p)= P(\bar{p})+ P_{p}\,\tilde{p}+ \frac{1}{2}P_{pp}\,\tilde{p}^2 + \dots , \qquad (4.16)$$

where $\tilde{p} = p - \bar{p}$. Averaging over time, we obtain $P = c_1 + c_2\,\overline{\tilde{p}^2}$, where $c_{1,2}$ — constants. Of interest is the quantity $\overline{\tilde{p}^2}$, which determines the dependence of P on the parameters of the magnetic field. From now on, the designation P refers specifically to this quantity. For the assessment, we will use the fact that relatively rapid fluctuations in the density $\tilde{p}$ do not cause a nonlinear response
protein, it does not have time to react by changing its conformation before
state that could be designated, for example, as "the gate is open." Therefore, it is natural to first average $\tilde{p}$ over some
time interval T of the order of the response time, and then calculate the mean square of the obtained value

$$P \sim \overline{(\tilde{p}_T)^2} . \qquad (4.17)$$

From the point of view of physics, time T is the measurement time or the accumulation time of changes in the probability density, the time during which
the protein "allows" the particle to be in phase with the MP
state. If this time is long, then the protein will notice only those changes that have accumulated over this time. In order for the changes accumulated over time
ωT changes were noticeable, there must be a slow component in the process of changing the probability density. That is, the frequency
external field must be close enough to the frequency of the interference maximum. Thus, it is clear in advance that the time T is a parameter
models associated with the width of the biological response by frequency.

Let us illustrate this with a simple example. Let us consider the behavior of the function $p(\omega_0,t)$ with $a_{mm} = 1$. Let us introduce dimensionless variables $\tau = \omega_0 t$, $h = H_{AC}/H_{DC}$, $\omega = \omega/2\omega_0$, then from (4.8) we find

$$p(\omega_0,t)= \cos m\omega_0 + t + \frac{1}{2}\frac{h}{\omega}\sin(2\omega t) .$$

In order to explain the general nature of the behavior of the probability density, we will consider the interference of angular states with magnetic quanta.

5The contribution of the following expansion terms is considered separately in Section 4.2.

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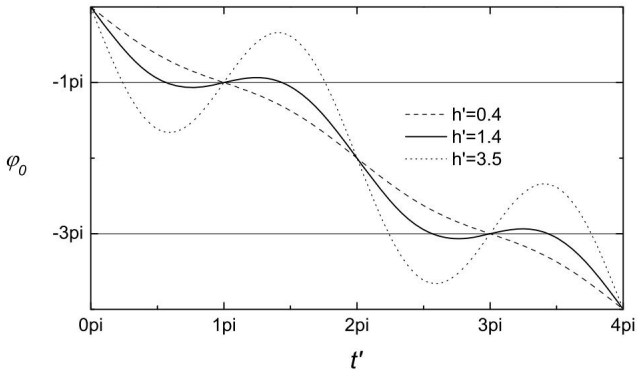


Fig. 4.4: Shift of the maximum of the ion probability density as a function of time t at frequency ÿ = ÿ and the relative amplitude h $\bar{}_{12}$ and different meanings of relative-

.

numbers differing by 1 and at a frequency ÿ = 1/2. This frequency, as will become clear below, corresponds to one of the maxima of angular mode interference. Up to an insignificant factor, the probability density is equal to

$$pm=1(ÿ0,t) = \cos(ÿ0 + t + h \sin t) .$$

This is only that part of the probability density that depends on the MP; it can take negative values. The angular position of the maximum of the probability density is then determined by the equation

$$ÿ0(t,h) = ÿt ÿ h \sin t .$$

This function for various values of the field amplitude h is shown in Fig. 4.4. It is clearly seen that, for a certain value of h, the maximum of the probability density remains almost motionless for a relatively long time. This is due to the fact that during this time the phase difference of the interfering modes remains almost unchanged. This is followed by a rapid shift of the maximum to an equivalent position, that is, a rotation through a full angle. Thus, the phase difference is, as it were, "frozen," and the density maximum hangs at a certain angular position. In the general case, when the field frequency does not exactly correspond to the frequencies of the interference maxima, the rapid rotation differs slightly from 2ÿ. Therefore, the sector corresponding to the maximum rotates slowly. This leads to the fact that, on average over a large time interval, p = Const.

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However, if the protein's reaction time to the probability cloud thickening
less than the period of this slow rotation, then the protein will have time
trigger. Then ensemble averaging or infinite time interval averaging should be
performed after taking into account the protein's response to density thickening.
At the same time, moving average, in order to smooth out
It is advisable to carry out relatively fast oscillations immediately.

Considering that, except in physically impossible cases,
$\overline{p} = \sum_m$ amm, for $p\tilde{}$ and for $p\tilde{}T$ one can use formulas (4.8) and (4.12)
respectively, where when summing over m, m we put m = m

$$p\tilde{}T = \sum_{m=m;n} amm \exp[imy0 + i(yz + n)yt] \frac{\sin[(yz + n)yT]}{(yz + n)yT} Jn(z). \quad (4.18)$$

To obtain P, (4.18) should be squared and averaged over
time interval T . It is clear that the expression for P will be contributed by
only those terms $p\tilde{}T \cdot p\tilde{}T$ that are products of complex conjugate terms (4.18). They do not
contain an oscillating time dependence, so during the final averaging their contribution

does not disappear. That is, in this case, the square of the sum (4.18) is reduced to
the sum of the squares of the individual terms. Therefore

$$P = \sum_{m=m;n} |amm|^2 \left[\frac{\sin[(yz + n)yT]}{(yz + n)yT}\right]^2 J2\,n(z). \quad (4.19)$$

The dependence on y0 disappeared, as expected. Indeed,
the angular position of the "gate" with respect to the spherically symmetric
potential should not play a role. After substituting the notations
(4.8), (4.10) we write down the resulting formula for the probability of dissociation
of the ion-protein complex (2yf =y)

$$P(f,HDC,HAC) = \sum_{m=m;n} |amm|^2 \times \left[\frac{\sin[b(m - m)HDCT + 2ynfT]}{b(m - m)HDCT + 2ynfT}\right]^2 J^2_n(m - m)\left[\frac{b}{2yf}HAC\right]. \quad (4.20)$$

■ The effect described by formula (4.20) is not a resonance, then
there is, it is not associated with the resonant transfer of energy from the oscillator
some modes into others. This is the effect of interference of quantum states
ion inside the protein capsule. Under certain parameters, magnetic field
interference leads to a condensation of the ion probability cloud at a certain
angular position. This condensation slowly shifts and, passing past the "gate,"
triggers the protein to change its size.

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4.1.2 Features of the state of the ion in the protein position

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The most common objection to the notation of Hamiltonian (4.1) is that it does not take into account the deviation from spherical symmetry.
potential of the connecting cavity and there are no terms describing
interaction of the ion with thermal vibrations of the binding ligands.

It was said above that, taking into account the size of the ion in the cavity, its potential mainly consists of a centrally symmetric part.
In the next approximation, the ion potential can be represented as
amounts

$$U(r)= U(r)+ ÿu(ÿ, ÿ) ,ÿ 1 .$$

In this approximation, the small octahedral contribution u(ÿ, ÿ) can be viewed as a constant perturbation of the Hamiltonian. Then each
the Zeeman sublevel of the ion would be split once again in
in accordance with the irreducible representation of the octahedron symmetry group. From the point of view of the model under consideration, this would lead to the emergence of a new quantum number numbering sublevels with the same
the value of the magnetic quantum number, and the need to carry out averaging over this number as well. The magnitude of this new splitting is much greater than the magnetic splitting. Therefore, the new quantum
number does not affect the interference of nearby states with different magnetic quantum numbers. Of course, the calculated spectra would be
changed, but only in minor details.

Magnetism-dependent interference also exists in the opposite approximation, when the central potential can be neglected.
and consider only the low-symmetry potential. This approximation is known as the crystal field approximation. It leads to the so-called freezing of the orbital momentum. The angular momentum of an atom
in a low-symmetry field it moves between several preferred directions determined by the symmetry of the potential,
so that on average over time the angular momentum is zero. The relative phases of the wave functions also take on a number of preferential
values. The additional MF makes some of them more probable and leads to interference. However, in this case, the MF-dependent
The interference part of the ion probability density is small in comparison with its constant part, defined as the fully averaged density. In the central potential, these parts have the same
the same order of magnitude. Therefore, the presence of a central potential in the Hamiltonian is necessary for significant interference

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effects, and the presence of a small low-symmetry potential is insignificant. Note that U(r) is included only in the coefficients amm in
formula (4.20). Therefore, neither the positions of the frequency spectrum peaks nor the amplitude spectrum depend on the exact form of the central potential. For example, it could have a maximum in the center of the cavity, thereby determining the equilibrium positions shifted toward the ligands.
ion. There is reason to believe that this type of potential is a more realistic model than a potential with a minimum at the center.

Another question is related to the presence of ion gates: do they distort to a significant extent the central potential of the ion? Ionic gates in The binding cavity is a convention intended to make it easier to visualize the processes of binding and dissociation. An ion can tunnel between any three adjacent ligands in the octahedron. Ionic
the gate is a local decrease in potential function in these places.
Since the leakage of an ion from a cavity occurs very rarely on the scale of quantum mechanics, with a characteristic time of 0.1 s, the indicated decrease the potential is very small. Therefore, it is possible to
assume that the gates do not disturb the ion potential. The probability of leakage is determined only by the exponentially small "tails" of the wave functions of the ion between ligands.

Apparently, the most important issue is the thermal fluctuations of the ligands. Let us first consider a simple one-dimensional model,
in which there is a spring connected to a fluctuating base.
At time t = 0, a particle with a certain mass is attached to the free end of the spring. Gradually, the particle will acquire random oscillations. The time T for establishing dynamic equilibrium depends on the spring stiffness. If the spring is soft,
then the process of establishing equilibrium can be very large. The dynamic state of the mass in the time interval <T is usually called
a metastable state, that is, a state far from thermodynamic equilibrium, but approaching it. In a metastable state, even small forces, compared to the scale of fluctuations,
can have a noticeable effect on the particle. Now let us assume that there is three-dimensional system, mass in potential U(r). Usually, the dynamics of such systems are described in so-called normal coordinates, which have
special properties. Excitation of the system along any of the
normal coordinates has no effect on the dynamics along other normal coordinates. It is now obvious that the process of establishing
dynamic, or thermal, equilibrium can have different speeds for different normal coordinates. For example, the normal per-

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belt A is in equilibrium with its fluctuating force, in
while the variable B is in a metastable state, then
is, is not thermalized and therefore easily controlled. Here we have
dealing with a single classical particle that is thermalized and
simultaneously not thermalized, according to different normal variables.
It can be said that thermal relaxation occurs at different rates depending on the type of connection between the particle and the random force.

There is a wide range of different energy relaxation times
in gases, liquids, and solids. Typically, at room temperature, relaxation times of the order of picoseconds are characteristic of the Cartesian coordinates of free particles, atoms, and ions placed in liquids. The relaxation time scale can be microseconds.

for electron spins, seconds for nuclear spins, and a whole range of specific times for the so-called collective variables in many-particle ordered systems, for example, in crystals. Biological
Membranes and other macromolecules are also systems where collective excitations are possible. They are often described in terms of
equations of quantum mechanics, demonstrating the general quantum properties state.

In quantum mechanics, normal modes of quantum oscillations
(eigenfunctions of the Hamiltonian) play the role of normal variables. For bound particles, normal modes usually represent
a discrete series of functions numbered by quantum numbers. The wave function of a particle in a central potential has a radial,
azimuthal and polar modes. So the wave function is factorized into three eigenfunctions. An external force excites different modes according to quantum selection rules. For example,
impulses of uniform, and even relatively strong, electrical
fields displace the ion, in a sense similar to what happens in collisions. However, they do not cause transitions between the Zeeman levels of polar modes due to the parity selection rules, in
while the transitions between radial and azimuthal states
quantum numbers can occur.

Returning to the general objection that a weak magnetic field, ÿc ÿT, is incapable of ,
controlling thermally perturbed ion dynamics, we note the following. This would be the case if the ion before leakage
was completely thermalized, that is, it was inside the cavity for a fairly long time. However, this is not the case. The ion gets
into the cavity at a certain point in time, after which the processes start
thermalization. Only two modes of ion dynamics, radial and azimu-

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tal, take part in rapid thermalization, since for these
mod lacks unfavorable selection rules. Soon after
the ion is in a thermalized state in the radial and azimuthal modes and in a
metastable state relative to the polar mode exp(imÿ), the level of which is
split in the magnetic field into Zeeman sublevels. This is precisely the state
that is described by Hamiltonian (4.1)
on an interval shorter than the relaxation time. In this state, there is no
need to introduce interaction with the thermostat into the Hamiltonian; it does not
affects the angular polar modes. The effect of this interaction on
other modes leads to a statistical distribution over their quantum numbers and is described
by the corresponding averaging. The relaxation time ÿL *of the phase difference* of the polar
modes, given the unusual geometry of the system, may be quite large, presumably on the
order of hundredths of a second. This is sufficient for the manifestation of interference
mechanisms. Of course, the idealization ÿL > ÿÿ1 adopted

in the model, should be considered only as an idealization. The validity of
its use is determined by the good agreement between the calculated
and experienced curves. At the same time, the reason for good performance
This idealization must be theoretically justified.

Another important question arises in relation to small magnetic
numbers, typically m < 3–4, are taken into account in the theory to achieve
good agreement with the experimental data. When the ion is within the
cavity at the initial moment of time, there is no reason for the ion to be in
the state described by
a separate eigenfunction of the Hamiltonian. It is in superposition of various
eigenfunctions. Mathematically, the effect
dissociation is determined mainly by small magnetic numbers
regardless of the actual energy distribution among angular modes and
modes of other quantum numbers. Large m indicate a fine-grained
interference pattern or a fine-grained distribution of the ionic probability
density. However, such a distribution does not
causes changes in dissociation. Formally, equation (4.20) allows us to
investigate what happens at large m. The dissociation effect is more
pronounced when the modes with large m are less populated.

The initial distribution of magnetic numbers depends on many
parameters of the binding protein and is hardly predictable. However,
It is certain that thermal disturbances of the potential cannot excite
states with large quantum numbers. The characteristic energy of vibration

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the order of magnitude of the ion's ratio is equal to

$$n2\,\frac{2}{MR2}\ ,$$

where n is the sum of the radial and azimuthal quantum numbers. Since, for example, for a calcium ion in the effective potential, the radial energy 2/MR2 is only two orders of magnitude less than ÿT ca 0.7 A^{o}, then in the conditions thermodynamic equilibrium, only states with quantum numbers of no more than a few units are populated. The magnetic quantum number does not exceed the azimuthal number in absolute value.

An electron in such a cavity would be in the ground state, thermal perturbations of order ÿT would not excite other states and, accordingly, interference would be impossible. Ions in an imaginary cavity of a larger size would be characterized by the excitation of states with large quantum numbers, interference would have would have a fine-grained structure and would therefore be unobservable. Surprisingly, the ion masses and the sizes of the binding cavities have values that ensure proportionality between the inhomogeneities of the interference pattern and the ion gates. This is precisely what allows us to observe interference.

4.1.3 Spectral peak width

Dependence of the probability of dissociation (4.20) on the amplitude of the variable components are contained in the argument of the Bessel functions. Dependence on frequency is contained in two factors. However, it can be argued that that the maxima of P are determined mainly by the zeros of the denominator of the fraction in (4.20), that is, by the equation ÿz + n = 0. The solution of the equation leads to the following relation for frequencies ÿmax close to the frequencies of the maxima P6

$$ÿmax = \frac{m}{}ÿc\ ,n = 1, 2, \ldots , 2n \qquad (4.21)$$

where ÿc = qHDC/Mc is the ion cyclotron frequency. Thus, the number of maxima and their intensity depend on the relative magnitude elements of the density matrix amm for levels with different values changes in the magnetic quantum number m.

It is possible to estimate the width of the maxima f, f = ÿ/2ÿ, taking into account note that the width of the function sin2 x/ x2 is approximately equal to ÿ, then

6Here and below the minus sign in the expression for the frequency spectrum is associated with the choice phases of sinusoidal MP, omitted.

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that is, the value x = ÿ determines the width of the peak. Considering that x = (ÿz+n)ÿT , and using the obvious relation [(ÿz+n)ÿT] f f = ÿ, we find f = 1/2nT. For example, for the peak at ÿmax = ÿc, as follows from (4.21), the terms of the sum (4.20) with m = 2n are suitable.
Of these, only the minor term n = 1 makes the main contribution to the peak width, so that for this peak f = 1/2T. Numerical calculations
show that this estimate is quite accurate, despite the fact that the second multiplier P, J2 n, also depends on f and can affect the width of the peaks.

The literature discusses the possibility of simultaneous participation of different ions in the response of the same biological system to a magnetic field with any fixed parameters. This can happen,
if the subharmonics and harmonics of different ions differ from each other smaller than the peak width in the response. In this case, the resulting spectral curve generally has a maximum at a frequency that does not coincide with the characteristic frequencies of any ion. The regular method
The division of contributions in this case consists of a simultaneous proportional increase in all three parameters of MP, HDC, HAC, f.

on-Let, for example, for fixed values of H(0) H(0) DC,H(0) AC,f(0)
observe extreme MBE. Most often, qH(0) DC/2ÿMc. AC =1.8H(0) DC,f(0) =
Let, further, the coefficient of proportional increase
is equal to k, that is,

$$HDC = kH(0)_{DC}\ ,HAC = kH(0)\ _{AC}\ ,f = kf(0)\ .$$

Then the level of the MBE from each of the ions, within the framework of the ion interference model, does not depend on k. At the same time, the relative width extremum of any ion

$$\frac{f}{fmax}\ \ddot{y}\ k\ddot{y}1$$

is inversely proportional to k. Thus, *the resolution of the spectral interference peaks of different ions improves with increasing*
intensity and frequency of the magnetic field. Fig. 4.5, constructed based on the data MacLeod, Smith, and Libow [564] illustrates this. In all cases, the field strength was chosen so that the cyclotron frequencies were equal to those indicated in the figure.

We also note that the model is constructed in the idealization of a small angular size of the "gate", compared to ÿT . Taking into account the finite size led would lead to some additional broadening of the spectral peaks. However, as will become clear from a comparison of theoretical predictions with experiment, this approximation is well fulfilled.

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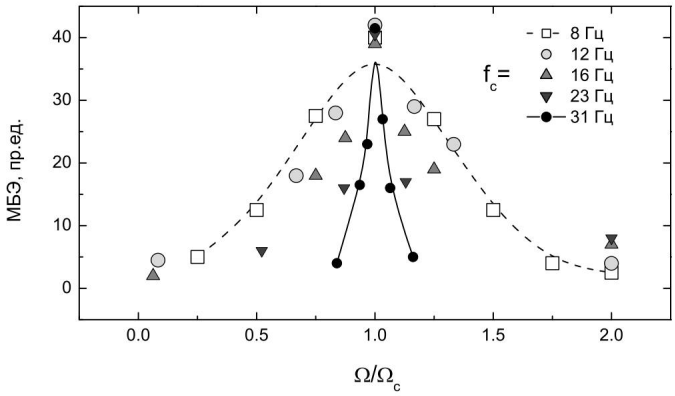


Fig. 4.5: Mobility of diatoms under the influence of a low-frequency alternating magnetic field with a frequency in the vicinity of the indicated cyclotron frequencies of the calcium ion. The standard deviation is about 3–5%, adapted from data [564].

Using the form of the wave function (4.5), we calculate the energy of the system:

$$ÿ(t)= ÿ|H|ÿ = ÿ0 ÿ Hz(t) \sum_{kmm} |aklm|\, 2ÿm ,$$

where ÿ0 is the energy of the system in the absence of MF, ÿm is defined by formula (4.3), and the basis functions are orthogonal with respect to all indices. Since ÿm = ÿÿÿm, then if, for example, the weights of the states ±m are the same, the energy ÿ is strictly constant. If the energy of a quantum system is constant, then How can the MP signal be transmitted through this system? This contradiction is related to the use of the semi-classical approximation, when quantum system interacts with classical electromagnetic field. If we used quantum electrodynamics, where EMF quantized, then states with different phases would correspond to states EMF with different numbers of photons. That is, there would be an exchange of energy between the particle and the field and no contradiction would arise. For the purposes of this For works where only the state of the particle is of interest, the semi-classical approximation is quite sufficient.

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4.1.4 Probability of dissociation in dimensionless quantities

exchangeable

To obtain the formula for ion interference in a convenient form with dimensionless arguments, we denote

$$h = \frac{HAC}{HDC}, \quad ÿ = ÿc\,\frac{ÿ}{} = \frac{f}{} = f, fc \tag{4.22}$$

that is, we introduce dimensionless parameters: the amplitude of the variable component of the magnetic field h and its frequency ÿ or f, measured in HDC and ÿc (or fc) respectively. In the new notations

$$ÿ = hÿ1, z = \frac{m}{2}\frac{h}{f}, \quad ÿz = \frac{m}{2}\frac{1}{f}.$$

Then formula (4.19) takes the following form

$$P = \sum_{mmn} |amm|^2 \frac{\sin 2A}{A2} J2_{\pi} \frac{m}{2}\frac{h}{f}, A = \frac{1}{2} m + nf ÿ. \tag{4.23}$$

Here

$$ÿ = ÿcT \tag{4.24}$$

— is the only quantity in formula (4.23) that depends on the properties ion and the properties of the protein binding site. Interestingly, the parameters of the ion, ÿc(HDC), and the protein, Ť, are included in the formula as dimensionless product characterizing the entire ion-protein complex. For the ion 40Ca2+ in MP HDC = 45 ÿT, with the dissociation time of the complex T =0.1 s [437] we get

$$ÿ ÿ 22. \tag{4.25}$$

It can be expected that the order of this value for other ions and complexes will not differ too much from (4.25), since for lighter ions it is natural to assume a shorter dissociation time, and on the contrary, for heavier ones it is greater.

The rate of interaction processes of calcium with binding centers was measured for several calcium-binding proteins by methods of 43Ca-NMR spectroscopy [437] and biochemistry [555]. For two for strongly binding centers the rate constant was ÿ 1–10 Hz, for two weakly coupled ones - more than 200 Hz.

Note that the position of the peaks of function (4.23) in the dimensionless variable f

$$f_{max} = \frac{m}{2n} \tag{4.26}$$

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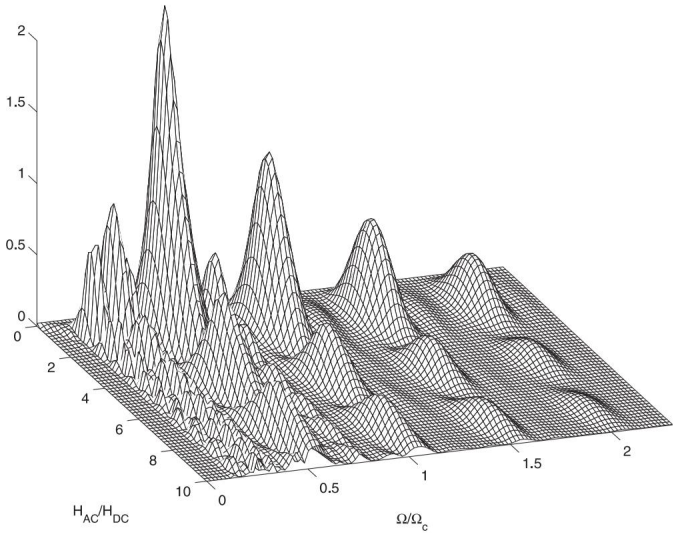


Fig. 4.6: General view of the surface P(h,f), calculated using the formula (4.23). The main interference maximum is at f = 1/2, h = 1.8.

fixed, which provides certain conveniences. Only the relative width of the frequency maxima depends on ÿ

$$\frac{m}{2} + nf\ddot{y} \qquad \ddot{y}\ddot{y} = \ddot{y}f = \frac{\ddot{y}}{n\ddot{y}} \cdot \qquad (4.27)$$

f

It follows that the relative width of the peaks is inversely proportional to the constant MF. Trillo, Ubeda et al. in [551] and Blackman, Blanchard et al. in [374] used a reduced MF of about three
ÿT and confidently observed a relatively wide maximum of the MBE,
presumably on protons. It was significantly more difficult to detect
such MBE in the geomagnetic field, see the work of Lednev, Srebnitskaya et al. [179], due to the fact that the position of the relatively narrow “resonance” floated in accordance with the diurnal variations of the GMF.

Figure 4.6 illustrates formula (4.23). It shows the surface

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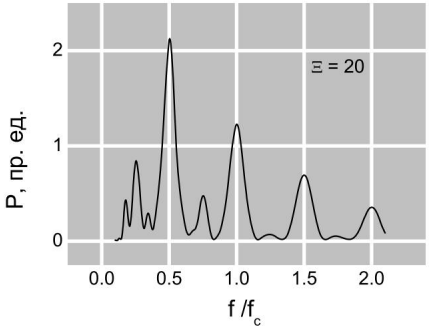


Fig. 4.7: Probability dependence probability of dissociation from frequency MP f at the optimal amplitude h = 1.8. The value of ÿ = 20 corresponds to the Ca- complex calmodulin.

the probability P(h,f), calculated according to the scheme 7

h (0–10)f (0–2.3)ÿ(21.68)m(ÿ2–2)n(ÿ3–3)amm (1.0) .

A series of peaks or maxima at different selected values of f formed by contributions of possibly several members of the sum (4.23) with different sets of numbers m, n. Thus, the series of maxima f = 1/2 formed by the contributions of members with m and n, corresponding to the equality m/n = ÿ1, that is, by several terms ÿ1/1, ÿ2/2, etc. All maxima of one series along the amplitude axis at a fixed value of f are formed simultaneously by all members of the sum participating in the series. The peaks of the series at a fixed value of the amplitude h formed by different groups of members of the sum. Figure 4.7 shows such a series for h = 1.8. The next figure 4.8 shows "decoding" of the maxima, which is obviously valid for any amplitude of the MP.

Since the elements of amm depend on the initial conditions of entry ion into the binding site, some of them may be much smaller in magnitude than others. This leads to the "cutting out" of terms with corresponding m, m, and m and the disappearance of some maxima frequency series. This remark is essential for explaining some experimental data.

Fixed field frequency

Sometimes, of the three characteristics of the external MP, HAC, HDC, ÿ, they fix the field frequency, not its static magnitude. In this case, it is convenient to introduce other dimensionless variables. Let us define the "Larmor" magnetic field H0

7See magnetic condition notations on page 57.

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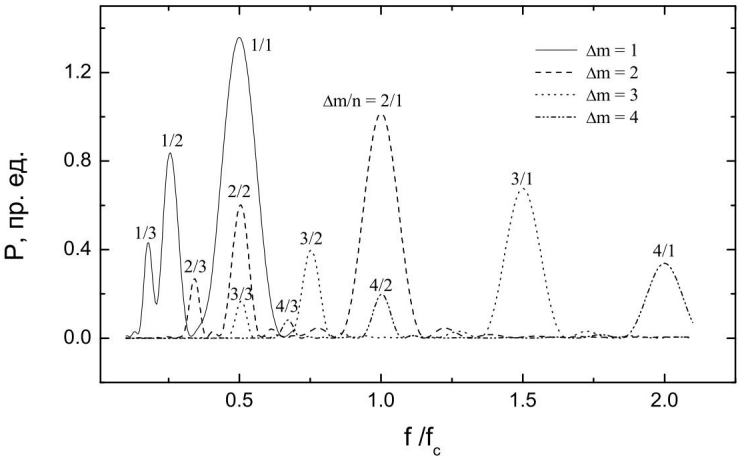


Fig. 4.8: Contributions of interfering angular modes to the probability of dissociation of the complex. The fraction near each peak shows which terms of the sum (4.23) it is formed by: the numerator is m, the denominator is n. the order of the corresponding Bessel function.

for a given ion and a fixed frequency ÿ, the following relationship
I eat

$$ÿ = bH0 .$$

This means that the Larmor frequency of an ion in a field H0 is equal to the frequency external field. We will also define new dimensionless parameters in in the following form

$$H = HDC/H0 ,h = HAC/H0 ,T = T ÿ .$$

Then the formula for the probability of dissociation takes the form

$$P = \sum_{mmn} |amm|^2 \frac{\sin 2A}{A2} J2\,n(mh) ,A = (mH + n)T .$$

For rotatable ion-protein complexes, see Section 4.5, A = [m(H +ÿ)+ n]T , ÿ =ÿ/ÿ — relative angular velocity rotation.

Further in the book, only previously defined dimensionless quantities are used. field parameters.

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4.2 Nonlinearity of protein response to density ion probability density

When considering the nonlinear dependence of the probability P of a biochemical reaction on the probability density p of the presence of an ion in a certain angular position were taken into account linear, its contribution is reduced to zero, and quadratic terms of the expansion (4.16). The question arises as to how general are the results obtained in the form of formula (4.19). Do they depend significantly on the form of the nonlinearity,

that is, depending on whether the following terms of the expansion are taken into account or not.

4.2.1 Estimation of the contribution of cubic nonlinearity

The corresponding effects, similar to (4.17), can be obtained from expression analysis

$$\overline{P3 \ddot{y} (\tilde{p}T)3}, \qquad (4.28)$$

Where

$$\tilde{p}T = \sum_{m=m;n} amm \exp[im\ddot{y}0 + i(\ddot{y}z + n)\ddot{y}t] \frac{\sin[(\ddot{y}z + n)\ddot{y}T]}{(\ddot{y}z + n)\ddot{y}T} Jn(z)$$

— expression (4.18) for the moving average of $\tilde{p} = p\ddot{y}p$, repeated Here for convenience.

In general, the terms of a triple product

$$(\tilde{p}T)^3, \qquad (4.29)$$

depend on the angle ÿ0. To obtain a result comparable with the experiment must be averaged over the angle ÿ0 ÿ [0, 2ÿ), which obviously gives zero. However, some of the terms do not depend on ÿ0. Among them, it is necessary to select terms that also do not depend on time. Then, when averaging over a large time interval, as follows from (4.18), their contribution to P3 does not disappear.

To distinguish between summation indices and other expressions related to different factors of the product (4.29), we provide them with superscript in brackets, that is, for example,

$$(\tilde{p}T)^3 = \sum_i \tilde{p}_T(i) .$$

From the expression for $\tilde{p}T$ it is clear that the terms of the sum should be selected

$$\sum_i \tilde{p}_T(i) = \sum_{i\,(mmn)(i)} ...$$

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c (i) m and n(i), which satisfy the relations

$$\sum_i (i)\, m = 0 \quad , \qquad \sum_i (\ddot{y}z + n)\,(i) = 0 \; . \tag{4.30}$$

In addition, all three factors

$$\frac{\sin[(\ddot{y}z + n)(i)\ddot{y}T\,]}{(\ddot{y}z + n)(i)\ddot{y}T}$$

in (4.29) should give maxima at the same values of ÿ, so
otherwise the contribution of this term will be small, that is, (ÿz + n)(i) =0, or

$$\ddot{y}k = \frac{\ddot{y}(i)\, m}{n(i)}\ddot{y}0 = \text{Const} \quad ,$$

for all i. Therefore, Const is a constant independent of i. Transforming this, we obtain

$$(i)\, m = kn(i) \quad , \tag{4.31}$$

where k is an integer, the same for all i. From which it immediately follows

$$\sum_i n(i) = 0 \; . \tag{4.32}$$

Note that the terms of the product (4.29), where at least one of n(i) is equal to zero, do not create a contribution, since then the ratio

$$\frac{\sin(\ddot{y}z\ddot{y}T\,)(i)}{(\ddot{y}z\ddot{y}T\,)(i)}$$

gives a surge only at ÿz = 0, that is, m = 0, but this value of m
is not included in the expression for $p_T^{\sim}(i)$ ·

The terms of the product (4.29) at the extremum points at frequencies ÿk are hold factors of the form

$$\prod_i Jn(i)\,(\ddot{y}n(i)\,/\ddot{y}) \; .$$

Since the absolute value of the Bessel functions is not greater than one, then among all the terms (4.29) one can distinguish a group of the most “weighty” ones, in which two of the three n(i) coincide. We will denote these quantities through n, and the remaining through n , the latter of the two quantities by virtue of (4.32)

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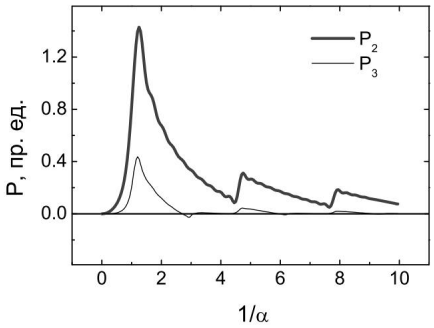


Fig. 4.9: Contribution to amplitude
MBE spectra from the quadratic,
— P2, and cubic — P3 nonlinearity in
response to change
probability density of the ion.

is equal to ÿ2n. The corresponding quantities, according to (4.31), (i) m designation
are m and m = ÿ2m. Thus, we can write the expression for
P3 at the points ÿk of extrema

$$P3(ÿ,ÿ)|ÿ=ÿk\ ÿ \quad \underset{n=0}{} \quad |a(kn)|\ 2a(ÿ2kn)J2\ n(ÿn/ÿ)Jÿ2n(2n/ÿ)\ .$$

Here the quantities amm and summation over m, m are replaced by single-index quantities
am and summation over m, since the expression
P depends only on m = m ÿ m. The entry a(kn) should be understood as
am, m = kn. In the last expression, summation over m is dropped, since the value
of P3 at the extreme points is considered,
when the relation of indices (4.31) is valid.

Previously, an expression for P (4.19) was obtained taking into account the quadratic term of the expansion (4.16). Let us now denote this value as P2, and find it values at the extremum points. From (4.19) we obtain

$$P2(ÿ,ÿ)|ÿ=ÿk\ ÿ \quad \underset{n=0}{} \quad |a(kn)|\ 2J2\ n(ÿn/ÿ)\ .$$

Since $J2_{-n} = [(ÿ1)nJn] \quad 2 = J2_n$ and Jÿ2n =(ÿ1)2nJ2n =J2n, then the indices
indicating the order of the Bessel functions can be written in absolute
size.

For an approximate estimate of the value of P3 in comparison with P2, we set all the coefficients that determine the initial conditions of the ion in the cavity of the macromolecule equal, that is, a ÿ 1. Graphs of functions

$$P2(ÿ)= \underset{n=0}{} J2\ |n|(ÿn/ÿ)\ ,\ P3(ÿ)= \underset{n=0}{} J2\ |n|(ÿn/ÿ)J|2n|(2n/ÿ) \quad (4.33)$$

are shown in Fig. 4.9, depending on ÿÿ1 = h = HAC/HDC, — the relative amplitude of the MF, |n| =1, .., 10. It is evident that the cubic nonlinear

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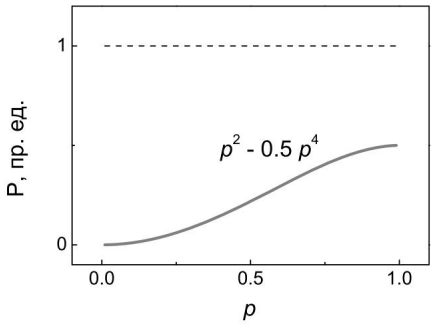


Fig. 4.10: Reaction probability protein as a function of the probability density of the ion: for large p 4th order nonlinearity is important with a minus sign.

In general, nonlinearity introduces only small corrections to those dependencies that are described by quadratic nonlinearity.

4.2.2 Contribution of fourth-order nonlinearity

A different situation arises when taking into account fourth-order nonlinearity

$$P4 \ddot{y} (\tilde{p}T)4 .$$

Reasoning similar to that used in the analysis of the contribution of cubic nonlinearity then leads to equation (4.32), in which the summation is over four values of the index (i). It is obvious that in In this case, this equation can be satisfied by choosing the same absolute value of n for all (i), which was not possible make for the sum of three n(i) · That is, two of the n(i) have value n, and two others have the value ÿn. It is easy to see that the sum of such terms, which obviously create the main contribution to P4, is simply equal to the square of P2, then There is,

$$P4 \ddot{y} P2_2 . \quad (4.34)$$

It is clear that if P2 is large enough, then the value of P4 cannot be neglected. It is very important that the sign of the coefficient in the fourth term order in expansion (4.16) can be negative, then the contribution P4 under certain conditions could compensate for P2. Indeed, the probability P(p) is bounded from above by one, therefore nonlinearity fourth order should manifest itself at sufficiently large values of p, Fig. 4.10. For the average probability of a biochemical reaction, then the following expression should be written instead of (4.17)

$$P \ddot{y} P2 + c4P2_2 . \quad (4.35)$$

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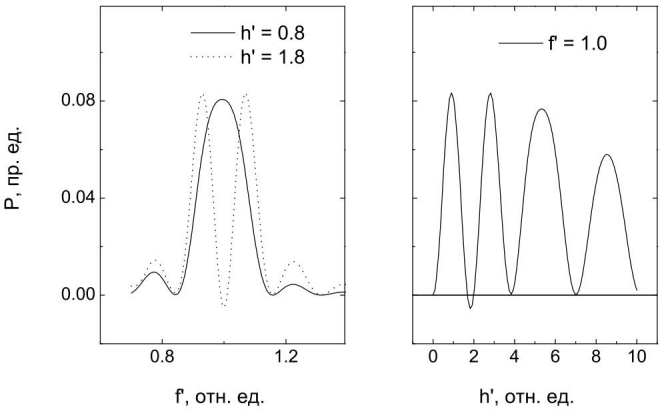


Fig. 4.11: Inversion of the maximum of the MBE at the cyclotron frequency with increasing field amplitude due to fourth-order nonlinearity; on the right is the amplitude spectrum at the frequency ÿc.

The coefficient c4 is negative because the tempo of the function P(p) must decrease with increasing p. The value of the coefficient c4 depends on the type of function P(p), that is, it is determined by the specific structure of the macromolecule and the binding cavity in it, the nature of the relationship between the biochemical properties of the macromolecule and the state of the ion, the state of the environment, etc. Due to the many factors that determine the type of dependence P(p), it is impossible to calculate the coefficient c4 in (4.35) theoretically. An idea of the best value of the coefficient in each specific case can be formed based on agreement with experimental

data.

Figure 4.11 shows the result of calculating the frequency and amplitude spectra using formula (4.35) for c4 = ÿ3.0, m =2, |n| =1, .., 4. It is evident that as the relative amplitude of the magnetic field increases from 0.8 to 1.8, the upper part of the maximum at the cyclotron frequency inverts, so that the effect at this frequency disappears or can have the opposite sign. In this case, a doublet with frequencies close to the cyclotron frequency appears. Recall that the value of P has the meaning of the MF-dependent part of the biochemical reaction probability, therefore negative values are permissible.

Similar behavior, the reversal of the maximum of the frequency spectrum near the cyclotron frequency for 45Ca ions in a field of HDC = 0.21 G with an increase in the relative amplitude of the magnetic field from 1.4 to 10.1, is observed

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Lieber, Rozek, and others in [332]. Achieving good agreement in the amplitude values has not yet been possible. The amplitude
spectrum due to the inversion of the main amplitude maximum at h = 1.8.

4.2.3 Dissociation as a Poisson process

Previously, when deriving formula (4.19), a moving average of the ion probability density fluctuations was used. The averaging time interval corresponded to the characteristic time T of the protein's nonlinear reaction. This choice had to be justified; it is not self-evident. Therefore, it is useful to consider another, physically transparent, method for obtaining the regularities described by the formula.

(4.19), although of a less general nature.

The starting point, in contrast to the hypothesis of a nonlinear protein reaction, (4.16), the assumption that the dissociation process has
the structure of a Poisson random process defined on a statistical ensemble of protein molecules. The probability that dissociation will not occur in the time interval [t ÿ T,t + T] is [512]
exp(ÿ2Tÿ), where ÿ has the meaning of the average density of the number of dissociations per unit of time. We will assume that the value of ÿ is proportional
probability density of an ion near the gate, that is,

$$\ddot{y} = \frac{cp(t)}{2T},$$

where T is the time scale and c is some proportionality coefficient. Considering the dependence of the probability density on time,
we write the probability of absence of dissociation in the form

$$\exp \ddot{y} \int_{t\ddot{y}T}^{t+T} \ddot{y}\, dt .$$

Accordingly, the probability of dissociation over time [tÿT,t+T]
has the form

$$P(t)=1 \ddot{y} \exp \ddot{y} \frac{c}{2T} \int_{t\ddot{y}T}^{t+T} p(\ddot{y}0,t)\, dt . \qquad (4.36)$$

Using definition (4.9), we write (4.36) as follows:

$$P(t)=1 \ddot{y} \exp (\ddot{y}cpT)= cpT \ddot{y} \frac{1}{2} c2p2 + \cdots . \qquad (4.37)$$

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Relation (4.37) determines the probability of dissociation over an interval time of magnitude 2T of the ion-protein complex formed at the moment time t ÿ T . For the i-th complex, the time moment t = ti is a uniformly distributed continuous random variable on the ensemble of molecules. To obtain the probability of dissociation,
related to experimental observations, it is necessary to average (4.37) over the random parameter t. In this case, the mathematical
the expectation coincides with the time average. Thus

$$P = M[P(t)] = P(t) = cpT \ddot{y} p\overline{2} \quad \frac{c2}{2} \overline{}_{T} + \dots . \qquad (4.38)$$

From (4.12) it follows that in physically significant cases, when ÿz + n =0, $\overline{pT} = 0$. Therefore, (4.38) coincides with (4.17) up to a coefficient.
and leads to the same formula (4.19).

Note that in this derivation of the formula, the assumption of a nonlinear reaction of the protein to the condensation of the probability density is not used. Instead, it was assumed that the dissociation process is a Poisson flow. This assumption, however, by virtue of expansion (4.37), always yields equal sign contributions to P from the nonlinearities of the second and
fourth order. Therefore, the conversion of the maximum into a minimum, or more precisely in a doublet, it is impossible. This small difference is important when observing reversal of the maximum of the MBE experimentally. It is clear that in this case the idea of a protein that actively reacts to
state of the ion, and not a passive lifeless system that provides only a Poisson flow of dissociations.

4.3 Interference in pulsed magnetic fields

There are many known experiments in the field of magnetobiology where pulsed magnetic fields were used. Pulsed fields of a wide variety of configurations are widely used in medicine for rapid healing of fractures and bone tissue growth [232, 262]. At the same time, the mechanisms of action remain unclear, and the level of reproducibility of the same experiments in different laboratories is insufficient. Below will be
pulsed magnetic fields of relatively simple form are considered, approximating a fairly large part of the fields used in practice.
It turns out that ion interference in such fields has its own interesting features [296]. In some cases, they are quite
correspond to known experiments.

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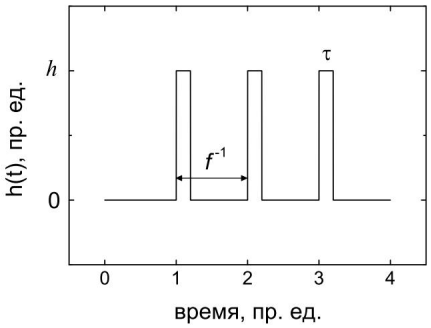


Fig. 4.12: Sequence rectangular pulses of MP with designation of the parameters. The pulse intensity is equal to ÿ = ÿh.

4.3.1 Parallel pulse and constant magnet-thread fields

It has been shown previously that an increase in the probability P of dissociation of the complex ion-protein is associated with the "freezing" of the phase difference of the angular modes of the ion wave function, Fig. 4.4. The idea of the mechanism of action of the MF pulse sequence is that the incursion of the phase difference of the angular mode over time t, associated with the term ÿ0t, that is, due to the presence of a constant MF, must be compensated by a change in the phase difference over counting the pulses of the alternating magnetic field h(t), see (4.6), (4.8)

$$p(\ddot{y}0,t)=\sum_{mm} amm \exp im\,\ddot{y}0 + \ddot{y}0t + b \int_0^t h(t)\,dt \quad . (4.39)$$

Let us write the pulsed magnetic field in the form of ÿ-pulses of intensity ÿ, following with frequency f

$$h(t)= \ddot{y} \sum_{k=\ddot{y}\ddot{y}}^{\ddot{y}} \ddot{y}(t \ddot{y} f \ddot{y}1k) .$$

Such a sequence approximates, for example, rectangular pulses Fig. 4.12 with period f and product ÿh = ÿ.

The phase difference incursion due to the constant field mÿ0t will be compensated if the pulses change the phase difference by the same amount of time. 2ÿrÿmÿ0t, r =0, ±1, ... One pulse appears in time f ÿ1. The phase shift due to the pulse, as follows from (4.39), will be mbÿ. Equating the phase shifts, we obtain the relation mbÿ = 2ÿr ÿmÿ0f ÿ1.

It connects the parameters of the magnetic field pulses with the magnitude of the local constant field and the parameters of the ion, through the coefficient b = q/2Mc, for

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obtaining the maximum P:

$$ÿ = \frac{1}{b} - \frac{2ÿr}{m} \cdot \frac{HDC}{f} \cdot \qquad (4.40)$$

Negative values of ÿ indicate opposite directions
constant and pulsed fields. At r = 0, rule (4.40) means compensation of the constant magnetic field by the constant component of the pulse sequence, that is, the appearance of a magnetic vacuum.
Smaller intensities, in modulus, although they may be formal
solution (4.40), do not lead to noticeable interference effects. In any case, the effective values ÿ of the pulse sequence are limited by the condition

$$|ÿf /HDC| > 1 .$$

High-intensity pulses are capable of rotating the phase by an additional angle of 2ÿr, which is insignificant for constructive interference. A more accurate result is as follows. We find the integral
from MP impulses

$$\int_0^t ÿ \sum_{k=ÿÿ}^{ÿ} ÿ(t ÿ f ÿ1k)\, dt = ÿ \sum_k ÿ(ft ÿ k) ,$$

where ÿ is the unit or theta function

$$ÿ(x)= \begin{matrix} 0, x ÿ 0 \\ 1, x> 0 \end{matrix}$$

Substituting into p(ÿ0,t) gives

$$p(ÿ0,t)= \sum_{mm} amm \exp im ÿ0 + ÿ0t + bÿ \sum_k ÿ(ft ÿ k) ,$$

where does it show that if

$$m bÿ =2ÿl , \quad l =0, ±1, .. ,$$

then p(ÿ0,t) coincides with (4.8) at HAC = 0, that is, with the case of interference in a constant MF, when the only maximum of P occurs
at HDC ÿ 0. Naturally, the pulses rotating the phases by 2ÿl do not change the behavior of the system.

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Let us consider the average over the time interval 2T = (t, t + nf ÿ1)

$$pT = nf \frac{1}{-1} \int_{t}^{t+nf\ddot{y}1\ 1} p(\ddot{y}0,t)\,dt = \frac{}{n}_{mm} amm \exp(im\ddot{y}0)\ \ddot{y}$$

$$\ddot{y}_{\ddot{y}} \int_{\ddot{y}}^{\ddot{y}+n} \exp ix\ddot{y} + iy \Big|_{k} \ddot{y}(\ddot{y}\ \ddot{y}\ k)\,d\ddot{y}\ , \quad (4.41)$$

where indicated

$$= m \frac{\ddot{y}0\ x}{f}\ ,y = m\ b\ddot{y}\ , \qquad \ddot{y} = ft. \qquad (4.42)$$

Introducing the auxiliary variable t = ÿ ÿ ÿ, we write the integral in (4.41) in the form

$$I = \exp(ix\ddot{y})\ I\ ,I = \int_{0}^{n} \exp ixt + iy \Big|_{k} \ddot{y}(t + \ddot{y}\ \ddot{y}\ k)\,dt\ .$$

Note that

$$\ddot{y}(t + \ddot{y}\ \ddot{y}\ k)_{k} = 1 + \ddot{y}(t + (\ddot{y}\ \ddot{y}\ 1)\ \ddot{y}\ k)_{k}\ ,$$

that is, the shift of a single staircase going up to the right, one step back, and one step up are equivalent. Then we get

$$\ddot{y}(t + \ddot{y}\ \ddot{y}\ k)_{k} = \ddot{y} + \ddot{y}(t\ \ddot{y}\ k)_{k}\ .$$

Then

$$I = \exp(iy\ddot{y})\ I\ ,I = \int_{0}^{n} \exp ixt + iy \Big|_{k} \ddot{y}(t\ \ddot{y}\ k)\,dt\ .$$

Next

$$\ddot{y}(t\ \ddot{y}\ k)_{k} \Big|t\ddot{y}(\ddot{y}1,0) = \ddot{y}(t\ \ddot{y}\ k)_{k} \Big|t\ddot{y}(0,1)\ \ddot{y}\ 1\ .$$

Denoting the left side of the last equality by ÿ, we transform the in-

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Tegral I:

$$I = \int_0^1 \exp(ixt)\exp[iy(ÿ + 1)]\,dt + \int_1^2 \exp(ixt)\exp[iy(ÿ + 2)]\,dt + \ldots + \int_{nÿ1}^{n} \exp(ixt)\exp[iy(ÿ + n)]\,dt =$$

$$= \exp(iyÿ) \prod_{l=1}^{n} \exp(iyl) \int_{lÿ1}^{l} \exp(ixt)\,dt \,. \quad (4.43)$$

Because

$$\int_{lÿ1}^{l} \exp(ixt)\,dt = \frac{2}{x} \exp[ix(l ÿ 1/2)] \sin(x/2) ,$$

then, making inverse substitutions in I,I ,I, we get

$$I = \exp i(x + y)ÿ + iyÿ\ ÿ\ i\ 2 \quad \frac{x}{} \quad \frac{\sin(x/2)}{2} S,\ S = x/ \prod_{l=1}^{n} \exp[i(x + y)l] . \quad (4.44)$$

Substituting into (4.41) gives

$$pT = n \quad \frac{1}{} \quad mm \quad amm \exp imÿ0 + i(x + y)ÿ + iyÿ\ ÿ\ i\ 2 \quad \frac{x}{} \quad \frac{\sin(x/2)}{x/2} S.$$

Calculating $P = pT \cdot \overline{pT}$, we note, as before, that only the complex conjugate terms of pT make a contribution that does not vanish when averaging over time. Considering that x ÿm, y ÿm, we obtain

$$P = \frac{1}{n2} \quad mm \quad |amm|^2 \quad \frac{\sin(x/2)\ x/}{2}^2 \quad SÿS.$$

The maximum of P is now achieved at x, y such that the quantity SÿS is equal to its maximum value (i.e., at x + y = 2ÿr, r = 0, ±1, ..). Substituting the values of x and y, we obtain the rule for the maximum of the effect under the action of pulsed MFs with pulse intensity ÿ and frequency f. It coincides, as it should, with (4.40). This simple rule for observing the MBE in pulsed fields gives another nontrivial prediction of the theory of bound ion interference. At r = 0, the maximum condition ÿf = ÿHDC means that the constant component of the pulse train compensates for the constant MF.

To estimate SÿS, we move from summation over l to integration

$$S = \prod_{l=1}^{n} \exp[i(x + y)l]\ ÿ \int_0^{2Tf} \exp[i(x + y)v]\,dv .$$

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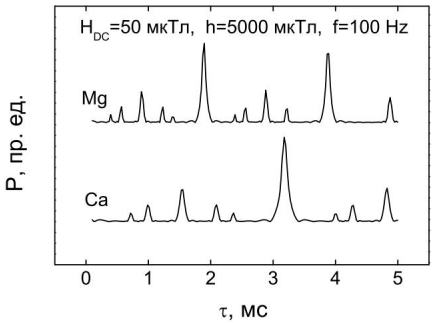


Fig. 4.13: Probability of dissociation of ion-protein com-

calcium and magnesium complexes in imp-

pulsed magnetic field depending on

dependence on pulse width.

However, in this case, an important property is lost: S(x + y)= S(x + y + 2ÿr),r =0, ±1, ... To save it, we write S in the form

$$S = \sum_{l=1}^{n} \exp[i(x + y + 2\ddot{y}r)l] .$$

Now, moving on to integration, we obtain the estimate SÿS

$$\int_{r=\ddot{y}}^{\ddot{y}} \left| \int_{0}^{2Tf} \exp[i(x + y + 2\ddot{y}r)v]\, dv \right|^2 = 4 \sum_{r} \frac{\sin 2[(x + y + 2\ddot{y}r)Tf]}{(x + y + 2\ddot{y}r)2} .$$

Thus, finally, the formula for P is

$$P = \sum_{mmr} |amm|^2 \left(\frac{\sin(x/2)}{x/2} \right)^2 \left(\frac{\sin[(x + y + 2\ddot{y}r)Tf]}{[(x + y + 2\ddot{y}r)Tf]} \right)^2 . \quad (4.45)$$

Fig. 4.13 shows the dependence of P for calcium and magnesium ions (fc = 76.6 and 126.3 Hz in a field of 100 ÿT, respectively) from the pulse duration ÿ at their fixed amplitude, calculated using the formulas

(4.45) and (4.42) according to the diagram

H(50)f(100)h(5000)T (0.07)m(ÿ2–2)r(ÿ6–6) .

The peak r = 0 common to both ions is not visible here, since the constant the component of the pulsed magnetic field has the same value as the constant field sign and their mutual compensation is excluded.

Special experiments aimed at identifying such

dependences of the MBE on the parameters of the MP pulses are unknown. Sometimes report the use of optimal parameters selected experimentally, which does not contradict the conclusions of this section.

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The pulse intensity ÿ can be realized in different ways. However,
in contrast to wide and low pulses, high and narrow pulses
of the same intensity hÿ induce noticeable eddy currents. This is associated with an increased likelihood of biological effects of a non-interference nature, thermal or electrochemical.

4.3.2 Interpretation of experiments with pulsed MP

The biological action of pulsed magnetic fields is often explained by electrical currents induced in biological tissue [454, 521, 455].
This mechanism predicts that bioeffects in some range
change in the same way as the induced currents in proportion to the time derivative of the magnetic field. At the very least, a correlation should be expected.
level of the induced electric field and the bioeffect it causes. Such a correlation was observed, for example, by Schimmelpfeng and Dertinger in [652], where cell proliferation was studied in a sinusoidal MF of 2.8 mT 50 Hz. Cell growth (human HL-60) occurred
only in those areas of uniform MF where the level of induced
electric field exceeded 4–8 mV/m. At the same time, many researchers note the discrepancy between such a prediction and the observed results in relatively weak low-frequency variable MF [496, 332, 642, 316, 491, 616]. For example, Ross in [642] used various MF satisfying certain “cyclotron”

conditions ÿf /b = HDC = HAC for calcium. The product fHAC,
that is, the level of the induced electric field was successively increased up to 40 times, but the statistically significant biological effect remained invariant. This indicates the existence

other mechanisms of biological action of weak MPs.

This section offers an explanation for the biological effectiveness of weak pulsed magnetic fields, which are insufficient to
cause electrochemical or thermal effects. Therefore, it is advisable to identify the range of MP parameters suitable for the discussed
interference mechanism.

There are many known rules and standards that establish maximum values for safe levels of exposure to variable magnetic fields.
Maximum levels of population exposure established by the standard
CENELEC 50166-1, comes down to a certain simple rule -
frequency f in the range of 1–1000 Hz and amplitude h of the sinusoidal MF

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must satisfy the relation

$$hf < kC = 3 \times 10^{4}\ \text{ÿT/s}. \qquad (4.46)$$

This value has only a conditional meaning, since the induced
The vortex electric field depends on the specific design of the magnetic field sources.
Level (4.46) can be understood as some good
average value. It is believed that lower exposures do not cause the usual
electrochemical or thermal effects. However,
such exposures may cause biological effects similar to
resonance [332, 283, 615, 245]. Therefore, it is natural to use the indicated limit in
relation to the interference mechanism so that
determine the conditions of its appearance.

This limit, together with other physical limitations, leads
to the inequalities that determine the values of static MFs in which complex spectra
of the MBE in pulsed MFs with two or more extrema can be observed.

As follows from the factor sin(x/2)/(x/2) in (4.45), the quantity x =
ÿ0f ÿ1m must be small enough. This means that the angular
shift of the interference pattern over time f beyond the $^{-1}$ should be less-
angular size of the gate ÿ ÿ/2. The MP pulse must return
pattern to its original position, accurate to the gate size.
That is, f ÿ $^{-1}$ < ÿ/2mÿ0, (formal solution of equation (4.40) at
=0 does not make sense, as is clear in advance). At the same time, the duration
momentum can be written in the form ÿ< 0.5 f ÿ1. Combining the last inequalities, we write

$$f^{-1} = \frac{\ddot{y}\ddot{y}}{2\ddot{y}0}, \quad \ddot{y} < 1 \text{ and } \ddot{y} = , \ddot{y} < 1 . 4\ddot{y}0 \qquad (4.47)$$

The relation (4.46) is valid for a sinusoidal magnetic field H(t)=
h sin(2ÿft), which induces an E-field E(t) ÿ hf cos(2ÿft). Thermal and electrochemical
effects are proportional to the averaged over
time to the square of the electric field, that is, E2(t) ÿ h2f 2/2. Let
the power level W limits this value, which is equivalent to the relation (4.46):

$$h2f\ 2/2 < W \ddot{y} hf < \ddot{y}\ 2W = kC . \qquad (4.48)$$

Let us now consider a pulsed magnetic field acting on the same biological system.
We write it as a Fourier series H(t)= a0/2+
$\sum_{n=1}^{N}$ an cos(2ÿnf t). The frequency spectrum of the pulsed MF should be

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is limited, otherwise the power of the induced electric field becomes infinite. Therefore, we assume that the MF pulses have a smoothed pulse shape of duration ÿ, and the frequency of the maximum harmonic N in the expansion is ÿ ÿ ÿ1, that is, N ÿ 1/ÿf. Now we find the value of E2(t). After several transformations, substituting the Fourier expansion coefficients an = 2h sin(ÿnÿf)/ÿn, we obtain

$$\overline{E2(t)\ \ddot{y}\ f}^{2} \sum_{n=1}^{N} a2\ nn2\overline{sin2(2\ddot{y}nf\ t)} = fh2/\ddot{y}2\ddot{y}.$$

Substituting W from (4.48) into the inequality E2(t) <W yields the relation hf /ÿ < kCÿ/ÿ2, or

$$hmax < kC\ddot{y}\ \ddot{y}/2f. \qquad (4.49)$$

It replaces the limit (4.46) in the case of a pulsed MF. Rule (4.40) determines the values of ÿ for a series of extrema of P. The difference ÿ = hÿ between the zero (r = 0) and first (r = 1) extrema is equal to 2ÿ/b. This means h = 2ÿ/bÿ if we change the magnitude of the momentum h and would like to observe two extrema on the h-dependence of the MBE. Since in all cases h<hmax must be true, we have, combining with (4.49), h<kCÿ ÿ/2f. Substituting the relation for h, (4.47), and the relation ÿ0 = bHDC,

we get inequality

$$HDC < (\ddot{y}\ddot{y}3)\ 1/4 \quad \frac{\overline{\ddot{y}2kC}}{32\ b}. \qquad (4.50)$$

The final limitation is that the angular shift of the interference pattern during the protein reaction time T in the absence of a pulsed magnetic field must be greater than the angular size of the gate ÿ ÿ/2. Otherwise, there would be nothing to compensate for with field pulses. This leads to another inequality ÿ0T > ÿ/2. With the best choice of ÿ = ÿ = 1, which corresponds to square-wave pulses, we obtain inequalities that determine the range of constant magnetic fields acceptable for observing complex ion interference spectra.

$$\frac{\ddot{y}}{} < HDC < 2bT \quad \frac{\overline{\ddot{y}2kC}}{32\ b}. \qquad (4.51)$$

The choice of optimal parameters for a pulsed magnetic field follows from the specified level of a constant magnetic field. First, the frequency ÿ0 = bHDC is found,

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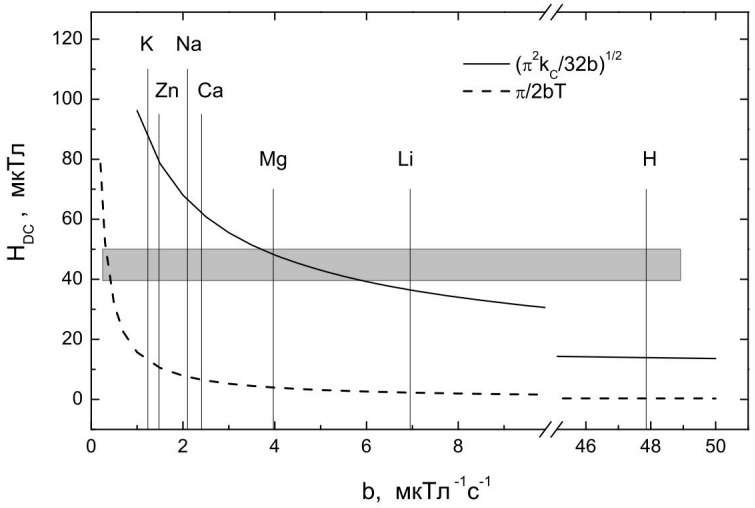


Fig. 4.14: Upper and lower limits (4.51) limiting the value of the constant magnetic field for measuring the polyextremal spectra of ion interference in pulsed magnetic fields, depending on the charge-mass ratio b = q/2Mc.

then f> 2ÿ0/ÿ, after that ÿ<f ÿ1/2, and finally h < ÿkC ÿ/2f.
Then it is necessary to make a fine adjustment of the found parameters in accordance with rule (4.40).

Inequality (4.51) means that not all ions characterized by the charge-mass ratio or the parameter b = q/2Mc are capable of exhibiting polyextremal spectra in a pulsed field. Figure 4.14 shows the b-dependences of the left and right limits in (4.51), which limit
the magnitude of the constant magnetic field. The values of b for different ions are also shown. It is evident that in the constant fields of the geomagnetic level of mid-latitudes 40–50 ÿT, K, Na, Ca, Mg, Zn ions are suitable for the mechanism under discussion, while light Li and H ions are outside the range and require reduction of the constant magnetic field. The interference mechanism can be observed even at fields greater than in (4.51), if not for the increasing the possibility of bioeffects of a different physical nature.

Rule (4.40) is not satisfied if the product of the pulse intensity hÿ and their repetition frequency f is less than the constant
MP HDC. In this case, the interference mechanism in the given here a specific scheme is not able to explain the biological effects

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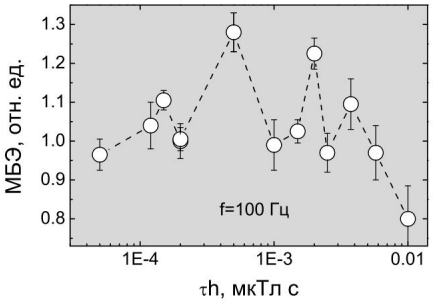


Fig. 4.15: DNA synthesis depending on the intensity the frequency of MP pulses, according to the data [391].

effects of pulsed fields. Similar effects of very weak pulsed MFs were observed, for example, by Berman, Chacon et al. in [369], Farrell, Litovitz et al. in [390]. In both works, hÿf ÿ 0.05 ÿT.

Takahashi, Kaneko et al. [391] observed extreme ion interference-like phenomena in a similar weak pulsed magnetic field. depending on three parameters at once: frequency, magnitude (amplitude) and pulse duration. The rate of DNA synthesis was studied in the Chinese hamster V79 cell culture by thymidine incorporation, labeled with the radioactive isotope hydrogen 3H. The experimental scheme is h(2–400)f(5–300)ÿ(6–125 ÿs)H(?)Hp(?). The polyextreme dependence of the magnitude of the effect on the pulse intensity is shown in Fig. 4.15. The frequency spectrum had two maxima in the region of 10–15 and 100 Hz. The characteristic value of the average magnetic field produced by the pulses, ÿhf, is close to 0.1 ÿT, which is one and a half orders of magnitude smaller than the value geomagnetic field. Therefore, it is impossible to connect this effect with the one under consideration. the model fails. However, the polyextremality of the curve indicates interference nature of the effect. Since the spectrum of this pulse sequence reached 40 kHz, it is possible that the interference pattern here was caused by fairly large electric fields induced in the medium.

In [486], Bersani, Marinelli et al. studied the redistribution of transmembrane proteins induced by pulsed magnetic field. on the cell surface at a constant magnetic field of 196 ÿT. A significant effect was reported with a triangular pulse shape of 50 Hz, so that hÿf ÿ 850 ÿT. This is a relatively large value compared to a constant field. The pulse shape is far from delta-burst, and the fundamental harmonic of the signal is close to the standard limit (4.46). Therefore, it is difficult to comment on these results from the point of view of ion interference. At the same time, there are no obvious contradictions.

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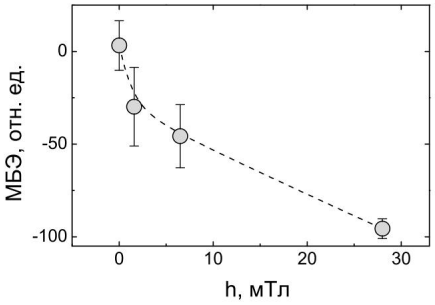


Fig. 4.16: Uptake of radioactive calcium tracer in thymocytes rat takh depending on the amplitude of 3 Hz meander pulses MP, according to [709].

Vallechek and Budinger [709] investigated the uptake of the 45Ca2+ label induced by concanavalin A added to a suspension of rat thymocyte cells. This parameter changed during 30 min of exposure to a pulsed magnetic field, and changes were observed only at a certain concentrations of added concanavalin (physiological window). In Under these conditions, the magnitude of the effect also depended on the parameters of the pulsed magnetic field. The magnetic field signal was rectangular, unipolar, with a frequency of f = 3 Hz and a 50% duty cycle (ÿ = 0.5/f). The pulse amplitude varied in the range h = 0–28 mT. Figure 4.16 illustrates the dependence of the effect on the pulse magnitude.

The amplitude of the alternating magnetic field in these experiments was 30 or more times higher than the level of the geomagnetic static field. Therefore, this effect cannot be explained within the framework of the ion interference mechanism, which requires an order-of-magnitude correspondence for the static field. fields HDC and the product fÿh of the pulsed MF.

On the other hand, all MP values used, except for the largest one, in this experiment were below the threshold level thermal effects of induced eddy currents, see (4.49).

Probably, the primary physical process that ensures the “engagement” of the MP with the biological system is associated with the action of the MP on the rate of reactions involving free radicals. This is indicated by both the suitable range of effective MPs in terms of intensity, and and a monotonic dependence of the effect on the intensity of the magnetic field. Unfortunately, the authors of this experiment did not report anything about the frequency selectivity of the observed effect, which could clarify the nature of this MBE.

Goodman, Bassett and Henderson found that some parameters of RNA synthesis in salivary gland cells exceeded the control level by 11–13 times after exposure to low-frequency (15 and 72 Hz) im-

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pulsed MP [454]. Significant differences in biological action
were observed for the specified fields, however, there was neither a sufficiently detailed description of the pulses nor an indication of the magnitude of the local static MF. Pulsed MF of 75 Hz induced a 2-5-fold increase
intensity of DNA synthesis in human osteoblast cells, as shown by Sollazo, Massari et al. [400]; MP has also been incompletely described.
However, it satisfied the standard hf < kC, that is, it fell within the range of the efficiency of the interference mechanism. RNA and mRNA synthesis increased 2–3 times compared to the control in T-lymphoblastoid cell lines that were irradiated with nearly rectangular 72 Hz MF pulses—the work of Phillips and McChesney [599].
The description of the MP is also insufficient for theoretical analysis.

Comparison of the theory with the majority of known experiments is difficult due to incomplete information about the MPs used. For example, only a third of the 27 reports [232] devoted to biological
and biomedical applications of pulsed magnetic fields, contained a careful description of the pulses. There were no reports using pulsed magnetic fields with a finely variable parameter. None of the reports mentioned the magnitude of the local constant magnetic field.

Comparison of the predictions of the interference mechanism with two experimental works [229, 248], containing sufficient
A full description of the MP is discussed in section 4.9.

■ Formula for the frequency spectrum of dissociation in a sinusoidal magnetic field (along a static field) predicts a rather uniform series
effective frequencies: ÿc, its harmonics and subharmonics. The ratio (4.45), on the contrary, predicts values that were impossible
would be identified *a priori* with some obvious frequencies. Therefore, rule (4.40) provides a simple way of its verification: *the biological effect should not change, within certain limits, when*
the amplitude of the pulses and their duration change so that their
the product remains constant. The same should be true for
change in the pulse frequency proportional to the applied constant magnetic field. We emphasize that rule (4.40) is strictly connected with the mechanism of dissociation due to the interference of quantum states
ion. Therefore, if the rule is satisfied, unambiguous conclusions about the physical nature of the observed effects are possible. The qualitative prediction is that biological effects of a pulsed magnetic field should be observed against a constant background for those ions,
for which similar effects are observed in parallel sinusoidal and constant magnetic fields or in a magnetic vacuum.

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4.3.3 Amplitude spectra for pulse modulation of MP

Let us consider the features of the amplitude spectra of dissociation arising in a sinusoidal magnetic field modulated by pulses turning the field on/off, Fig. 2.17. We write the magnetic field as follows:

$$H(t)= HDC[1 + h \cos(ÿt)M(t)] ,$$

where M(t) is the modulating function. Again, we start from the notation of the probability density of an ion at a certain value of the angular coordinate

$$p(ÿ0,t)= \sum_{mm} amm \exp im\, ÿ0 + ÿ0t + ÿ1 \cos(ÿt)M(t)dt .$$

Let us represent the function f(t)= cos(ÿt)M(t) in the form of a Fourier series, considering the period ÿ of the modulating function to be a multiple of the period 2ÿ/ÿ of the sinusoidal MF. This weak, from a physical point of view, limitation makes function f(t) is ÿ-periodic. Assuming also that M(t) is an even function and denoting ÿ = 2ÿ/ÿ, we write

$$f(t)= \sum_{k=1}^{ÿ} ak \cos(kÿt) ,ak = ÿ \frac{2}{ÿ} \int_{ÿ/2} f(t) \cos(kÿt)dt . ÿÿ/2 \qquad (4.52)$$

Then the integral in the expression for p is easily calculated and can be written equality

$$\exp im\, ÿ0 + ÿ0t + \frac{ÿ1}{ÿ} \sum_{k=1}^{ÿ} ak \frac{\sin(kÿt)}{k} =$$

$$= \exp[im(ÿ0 + ÿ0t)] \sum_{k=1}^{ÿ} \exp imÿ1ak \frac{\sin(kÿt)}{kÿ}$$

Using the following notation and equality

$$zk = m \frac{ÿ1}{kÿ} ak , \exp[(izk \sin(kÿt)] = \sum_{n} Jn(zk) \exp(inkÿt) ,$$

let's rewrite the infinite product in the last expression as

$$\prod_{k=1}^{ÿ} eizk \sin(kÿt) = \sum_{n} Jn (z1)ein^{1ÿt} \sum_{n} Jn (z2)ein2ÿt ...$$

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It can also be written differently

$$\prod_{nnn\ldots} J_n(z_1)J_n(z_2)J_n(z_3)\cdots = e^{i\psi t(1n+2n+3n+\ldots} \qquad (4.53)$$

Obviously, in the general case, the infinite product of Bessel functions is equal to zero, since $|J_n| \le 1$. One of the main contributions to (4.53) will be created by terms with $n = 0$, $n = n = \cdots = 0$, and even then only if the quantities $z_2, z_3, \ldots$ are close to zero, then $J_0(z_k) \to 1$.

Let us show that such an infinite product has a finite non-zero value. We will find the coefficients a_k of the above Fourier series. As already stated, the period of the modulating function is chosen to be a multiple of the period of the sinusoidal MF $2\pi/\omega$. The time interval of the MF on-time τ is also conveniently expressed in these units. We write the following definitions

$$\tau = s\,2\pi/\omega \,, \omega = r\,2\pi/\omega \,,$$

where s is a positive integer and $0 < r < s$ is a real number. Then calculating the coefficients (4.52) gives

$$a_k = \frac{2}{\pi\omega} \left[\frac{\sin(k/s - 1)r\pi}{(k/s - 1)} + \frac{\sin(k/s + 1)r\pi}{(k/s + 1)} \right] . \qquad (4.54)$$

For large values of k, we can write the relation

$$a_k \approx \frac{2}{\pi\omega} \left[\frac{1}{(k/s - 1)} + \frac{1}{(k/s + 1)} \right] < \frac{4s}{\pi\omega k} .$$

Therefore, starting from some number $k = K$, the inequality is valid

$$z_k = m \left| \frac{\omega_1}{k\omega a_k} \right| < m\,k\omega \frac{\omega_1}{\pi\omega k} \frac{4s}{} < \frac{1}{k} .$$

Since when $z_k \to 0$

$$J_0(z_k) = 1 - z_2\, k/2 + o(z_3\, k) > 1 - 1/k_2 \,,$$

then the infinite product of Bessel functions under consideration has a finite value

$$\prod_{k=K}^{\infty} J_0(z_k) > \prod_{k=2}^{\infty} J_0(z_k) > \prod_{k=2}^{\infty} (1 - 1/k_2) = 1/2 .$$

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Returning to the relation (4.53) and leaving the specified basis in it,
the main contribution, we write the probability density of the ion in the form

$$p(ÿ0,t)= \sum_{mm} ammeimÿ0\ eimÿ0t \sum_{n} Jn\ (z1)eiÿn\ t = = \sum_{mmn} ammeimÿ0\ Jn(z1)eiÿt ,$$

Where

$$ÿ = mÿ0 + ÿn .$$

Moving averaging is reduced to averaging the last exponential

$$T\ [eiÿt]= eiÿt\ sin(ÿT)/ÿT .$$

The average over time t of the square T 2[p(ÿ0,t)] consists of the sum of the products of the complex conjugate terms. Thus, the probability
dissociation of the ion-protein complex is equal to

$$P = \sum_{mmn} |amm|^{2} \frac{sin2(ÿT)}{(ÿT)2} J2\ n(z1) . \qquad (4.55)$$

The condition of maxima P, ÿ = 0, after substituting ÿ gives the spectrum of effective frequencies of the modulating pulse sequence

$$ÿmax = \frac{m}{n} ÿ0 = \frac{m}{2n} ÿc .$$

It is evident that the fundamental frequency of the MF spectrum must satisfy the same condition as the MF frequency when exposed to an unmodulated sinusoidal MF (4.21). This ensures the limit transition to the previously obtained formula for the effective frequency spectrum, when
the parameters of the modulating signal are such that the MP becomes sinusoidal soidal.

The dependence on the parameters of the modulating function is determined also the argument z1 of the Bessel function in (4.55), which after substituting a1 from (4.54) takes the form

$$z1 = \frac{mh}{2ÿf} \left[\frac{sin(1 ÿ 1/s)rÿ}{(1 ÿ 1/s)} + \frac{sin(1 + 1/s)rÿ}{(1 + 1/s)} \right] .$$

Here it was taken into account that ÿÿ =2ÿ and ÿ1/ÿ= h ÿc/2ÿ = h /2f , where, as well as previously, h = HAC/HDC, f = ÿ/ÿc = f /fc — relative amplitude

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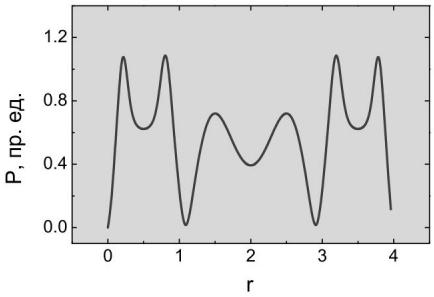


Fig. 4.17: Typical dependency dissociation probability bridge from the length of the switching interval (in units r) of sinusoidal MP with pulse modulation.

and the frequency of the sinusoidal magnetic field. In the case of a purely sinusoidal magnetic field we should set ÿ = ÿ =2ÿ/ÿ or r = s =1. Then

$$z1 = \frac{mh}{2\ddot{y}f} \lim_{\ddot{y}\ddot{y}0} \frac{\sin \ddot{y}\ddot{y}}{\ddot{y}} = \frac{mh}{2f} .$$

Thus, formula (4.55) in the limiting case of an unmodulated sinusoidal MF goes over to formula (4.23), obtained specifically for this case.

Formula (4.55) yields a polyextremal dependence on the parameters of the modulating signal. For example, the dependence of P on the interval r
The inclusion of the MP has the form shown in Fig. 4.17. Fig. 4.17 was obtained calculation with the following parameters: h = 11 (when a purely sinusoidal signal gives an effect close to zero), f =1, ÿ=6 (corresponds to the reaction time T =0.1 s of protein with calcium at HDC =0.1 Gs),
s =4 (one period of the modulating function is equal to four periods sinusoidal signal). A characteristic feature of such dependencies is their symmetrical appearance with respect to the point r = s/2. This provides a convenient opportunity for experimental verification.

Above we considered the case when non-zero products Bessel functions in (4.53) were determined mainly by the first coefficient of the expansion (4.52). This is true when the period ÿ and the interval ÿ of the modulating function are close, in order of magnitude, to the period of the sinusoidal signal. Another case is also possible when the period
ÿ 2ÿ/ÿ, that is, s 1. In this case, only the coefficient ak=s has the greatest and fundamental meaning. As follows from (4.54), it is equal to ak=s ÿ (2/ÿÿ)rÿ = r/s. The remaining ak, and with them zk, are close to zero. Then the main contribution to (4.53) is created by products with values of in- n(s) = 0, dexes n =0, n =0 ... for P in this , n(s+1) = 0,... . Derivation of the formula case repeats the previous one with the difference that instead of z1 should be substituted with zs, ÿ should be substituted with sÿ. After the index

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n(s) , along which the summation is carried out, we leave the symbol n. Then

$$P = \sum_{mn} |amm|^2 \frac{\sin 2(\ddot{y}T)}{J2\, n(zs), \ddot{y} = m\ddot{y}0 + sn\ddot{y}(\ddot{y}T)2}, \quad zs = m \frac{\ddot{y}1}{s\ddot{y}} \frac{r}{s}. \tag{4.56}$$

The last definitions for ÿ and zs can also be written as

$$\ddot{y} = m\ddot{y}0 + n\ddot{y}, zs = \frac{mh}{2f} \frac{r}{s}.$$

The first of them determines the frequency spectrum (ÿ = 0), which, as for pure sinusoidal signal, equal to

$$\ddot{y}max = \frac{m}{2n} \ddot{y}c.$$

Second, the argument of the Bessel functions contains a dependence on the parameters r, s of the modulating function. Again, for r = s (purely sinusoidal MF), we have formula (4.23).

Formulas for combined ones are derived in a similar way.
MP with harmonic modulation.

In [641] Litovitz, Penafil et al. used pulse-modulated MF to observe the effect of changes in enzyme activity. The period of the modulating function was 1 s at f = 60 Hz,
HAC ÿ HDC ÿ 0.1 G. In this case, s ÿ 60, h ÿ 1. We can assume that that the frequency f was close to one of the effective frequencies of the spectrum (4.56), that is, the condition m/f ÿ 2n is satisfied. Dependence on the pause l = s ÿ r between the intervals of switching on the MP, predicted by formula (4.56), could then have a form close to

$$J2\, n(nr/s) = J2\, n[n(1 \ddot{y} l/s)].$$

This dependence gives a decrease in P with increasing pause, which could explain a decrease in enzyme activity under these conditions, see Fig. 2.17.

■ The mechanism of ion interference is nonlinear in the sense that the sum of the magnetic signals a + b, which individually cause
reactions of magnitude A and B do not cause a reaction of magnitude A + B.
In particular, when exposed to a pulsed magnetic field, the response is not reduced to the sum of the responses from each of the signal harmonics. Therefore, the nature of the predictions of any of the "resonance" models, in particular, the parametric resonance model of ions, which necessarily takes into account only
one subharmonic, namely, the one whose frequency coincides with the Larmor frequency of the Zeeman splitting, is dramatically different from

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predictions of the ion interference model, which takes into account the full pulse shape and predicts the appearance of response maxima
depending on the intensity of the pulse even when none of the
harmonics of the signal does not coincide with the Larmor frequency. Thus,
it becomes possible to establish what the effect observed in the experiment is connected with: resonant transitions in the Zeeman multiplet or interference effects.

4.4 Inclined configuration of magnetic po- lei

The tilted orientation of the variable and constant magnetic field components is used quite often in experiments, apparently due to its simplicity. A solenoid, vertical or horizontal, is sufficient to create an alternating field. The role of the constant magnetic field is usually played by the geomagnetic field. The geomagnetic field vector in the Northern Hemisphere is directed downward at some angle to the horizontal.

At the same time, with this orientation it is difficult to explain the experimental results. Difficulties arise when trying to consider the results within the framework of any model representations. Let,
For example, they have in mind a physical phenomenon or mechanism whose model takes into account only a uniaxial magnetic field. Then the question of choosing the principal axis arises. With which particular pair of magnetic field components should the observed effect be associated, Fig. 4.18? Should the projection of the alternating magnetic field BAC onto the direction of the constant field or, conversely, the projection of the constant field BDC onto the direction of the alternating field be taken into account? Data
the options give different ratios of the values of the coaxial components, but it is this ratio that is the parameter of promising theoretical
mechanisms.

Blackman, Benan, and others discussed this issue in [480], although, from the point of view of From a physics perspective, it is incorrectly stated. The observed effect should be associated not with two parameters, BAC and BDC, but with three: the magnitudes of the fields and the angle between them. The question of the actual mechanism
phenomenon and the extent to which this mechanism allows for an idealized description using only two parameters lies beyond the scope of this
a priori choice. This circumstance is often overlooked when calculating,
for example, the cyclotron frequency of an ion taking into account only one component of the constant field parallel to the vector of the alternating magnetic field [643]. This
makes sense only if the primary target of the MP is

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gives anisotropy, that is, utilizes some other vector as
support vector, and all individual molecular targets of biological
systems are aligned in the same direction. Of course, the vector of variable
The magnetic field cannot be such a reference vector, since both alternating and
constant magnetic fields have the same physical nature. A suitable situation could
arise, for example, in the stem of some
plants oriented by the gravity vector. Can ions,
related to any primary target of the MP, to separate the components of the constant
MP, that is, to “know” about their presence? This is the question
experiment; such data are currently unknown. Therefore, the best a priori choice is
to take into account the full vector of the MP.

The experiment observes the effectiveness of both parallel and
and perpendicular orientation of the MP. Moreover, the effectiveness of both
orientations was observed in the same biological system,
[398]. This indicates the advisability of simultaneously taking into account both of
these possibilities within the framework of a single model. For the mechanism of ion
interference, this means that the probability of dissociation of the complex is
a function of four quantities, the variable and constant components of the MF, the
angle between them, and the frequency of the variable component. Within the
framework of the idealizations used in Section 4.1, such a problem is solvable.

The choice of the z-axis of quantization is unimportant. The observable quantities formed by quantum mechanical averaging |..| do not depend on it. There is a complete analogy with the choice of a coordinate system in classical physics. The eigenfunctions of an ion in a constant magnetic field generally depend on the angle between the z-axis and the direction of the constant
fields. It is more convenient, as usual, to direct the z-axis along the constant
components of the MP and avoid the dependence of these functions on the angle Vector
the oscillating variable magnetic field is then decomposed into a coaxial
constant field component and the one perpendicular to it. We will consider the
action of the perpendicular component separately, and then we will find out in
In what cases is it possible for a joint action with a parallel component to occur,
which cannot be reduced to a simple sum of effects.

4.4.1 Interference in perpendicular fields

MBE with perpendicular orientation of constant and variable
fields are usually associated with mechanisms such as magnetic resonance,
since it is for such resonances that perpendicular components are essential. A constant magnetic field splits quantum
particle levels into Zeeman sublevels, and the alternating field leads to transitions in the sublevels (the coaxial field does not cause transitions).

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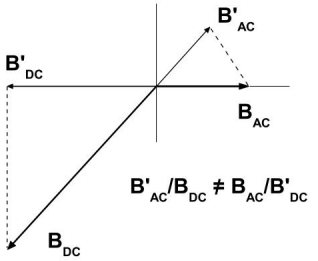


Fig. 4.18: Different selec-
ru parallel components of variable and
constant MP from-
The different magnitude of their ratio is an
important parameter of the theory.
ria.

the particle moves from the upper sublevel to the lower one, releasing energy absorbed presumably during the biochemical reaction. Since it is clear in advance that this energy is many orders of magnitude less than ÿT, we are , limited by the hypothesis that the biochemical reaction is somehow unknownly connected with the aforementioned transitions. Further, the matter is not
It seems that no formulas linking the biological effect to the magnetic field parameters could be obtained. Such reasoning, at best, yields a model predicting transition frequencies proportional to the constant field, that is, cyclotron frequencies for

of certain hypothetical ions. The dependence of the effect on the amplitude of the alternating field in such a mechanism is monotonic. Taking into account relaxation processes leads to the saturation effect
quantum transitions with increasing amplitude of the alternating field. Obtain
a decrease in the probability of transitions with increasing amplitude is impossible, and this does not agree with frequent observations of polyextremal dependences of the MBE on the amplitude of the alternating field.

Following the recipes of the ion interference mechanism, we will associate the MBE in perpendicular fields not with the fact that the ion goes into
or another state of the quantum spectrum, but with the fact that as a result of transitions the angular distribution of its probability density changes. We will
assume that the levels are Zeeman levels, and the transitions between them are caused by a perpendicular magnetic field with a frequency ÿ close to resonance.
Let the wave function of the system be found in the form

$$\sum_{\{i\}} c\{i\}(t)\, ÿ\{i\} \exp ÿiÿ\{i\}t/ , \qquad (4.57)$$

where ÿ{i} are the basis functions (4.4), and {i} is the set of quantum numbers

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k,l,m. Then the equations for the coefficients take the known form

$$ic\ddot{y}\{i\} = \sum_{\{i\}} c\{i\}\ddot{y}\{i\}|V(t)|\ddot{y}\{i\} \exp \ddot{y}i(\ddot{y}\{i\} \ddot{y} \ddot{y}\{i\})t . \quad (4.58)$$

It is clear in advance that only the coefficients will change over time.
Zeeman levels within each of the series with fixed values of the radial and azimuthal quantum numbers k, l. A low-frequency field cannot induce transitions with a change in these numbers.

Therefore, the quantum numbers k,l are here the solution parameters and
they can be omitted until averaging is needed
by states with different k,l. To identify possible effects, it is sufficient to obtain results for a three-level system. Let the numbers
m resonant states have values m = ÿ1, 0, 1

$$ic\ddot{y}m = \sum_{m} cm\ \ddot{y}\{i\}|V(t)|\ddot{y}\{i\} \exp (i\ddot{y}mm\ t) . \quad (4.59)$$

Let us represent the interaction operator associated with the MP variable in view

$$V(t)= Fe\ddot{y}i\ddot{y}t + Gei\ddot{y}t \text{ where } , \quad (4.60)$$

F = G+ are Hermitian conjugate time-independent operators
Tori.

The interaction operator of the orbital magnetic moment of an ion with MP has the form, see (4.1)

$$-\frac{q}{2McLH}, \qquad L = \ddot{y}ir \times \ddot{y} .$$

In the so-called precessing magnetic field, containing a rotating in-plane
z = 0 component

$$Hx = HAC \cos \ddot{y}t,\ Hy = HAC \sin \ddot{y}t,\ Hz = HDC ,$$

the interaction operator is equal to

$$V0 + V(t) .$$

In the previously adopted notations, these operators are equal

$$V0 = i\ddot{y}0 \frac{\ddot{y}}{\ddot{y}\ddot{y}} , V(t)= \ddot{y}\ddot{y}1(Lx \cos \ddot{y}t + Ly \sin \ddot{y}t) .$$

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The operator V0 splits the levels degenerate in the absence of an MF into Zee-man multiplets. The time-dependent operator V(t) causes transitions in the levels of the multiplets. This operator can be conveniently written as in the following form, see Appendix 6.1,

$$V(t)= \ddot{y}\ddot{y}1 \frac{}{2} \; L+e\ddot{y}i\ddot{y}t + L\ddot{y}ei\ddot{y}t . \qquad (4.61)$$

The case of a linearly polarized alternating magnetic field, oscillating along one axis perpendicular to z, is reduced to the sum of operators (4.61) with opposite signs of the frequency ÿ. Comparing (4.61) and (4.60), we note that the operator F is equal to

$$F = \ddot{y}\ddot{y}\frac{1}{2}\,2L+ = \ddot{y}\ddot{y}\frac{1}{}\,ei\ddot{y}\;\frac{\ddot{y}}{\ddot{y}\ddot{y}} + i\cot\ddot{y}\;\frac{\ddot{y}}{} \quad . \qquad (4.62)$$

Let's find its matrix elements. The wave functions of the central potential

$$\ddot{y}klm = Rkl(r)Ylm(\ddot{y}, \ddot{y}) \qquad (4.63)$$

are products of radial functions and orthonormal spherical functions, eigenfunctions for the operator of the square of angular momentum L2 and its projection Lz. Since the operator F acts only on variables ÿ, ÿ, its matrix elements can be found in the facings Ylm(ÿ, ÿ), assuming that the radial functions are normalized to unity, R..|R.. =1. The matrix elements of the operator L+ were found, for example, in [122]. They are non-zero for transitions with increasing m by unity and without changing l. Therefore, we write the matrix elements of F as follows

$$Fm,m\ddot{y}1 = 2\,2\;\frac{\ddot{y}\ddot{y}1}{}\;Ylm|L+|Yl,m\ddot{y}1 = \frac{\ddot{y}\ddot{y}1}{}\;\overline{(l + m)(l \ddot{y} m + 1)} . \qquad (4.64)$$

Let us note that

$$F10 = F0,\ddot{y}1 = 2\;\frac{\ddot{y}\ddot{y}1}{}\;\overline{l(l + 1)} .$$

After a series of simple transformations, which also take into account that $Gnm = F\ddot{y}_{mn,}$ $\ddot{y}mn = \ddot{y}m+1,n+1$, we obtain from (4.59), (4.60) the equation

$$ic\ddot{y}1 = F10e\ddot{y}itc0\;ic\ddot{y}0 \;,$$
$$= F10\;e\ddot{y}itc\ddot{y}1 + eitc1 \;,$$
$$ic\ddot{y}\ddot{y}1 = F10eitc0 \;,$$

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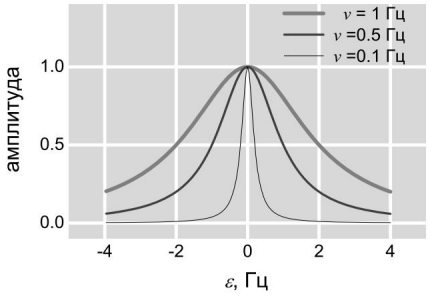


Fig. 4.19: Dependence of the amplitude of population oscillations quantum state from detuning at different values intensity of the "forcing forces."

Where

$$= ÿ01 + ÿ . \qquad (4.65)$$

Substitution

$$x = \exp(it)1 \,, y = \exp(ÿit)cÿ1 \,, z = c0$$

gives equations that we write in matrix form:

$$uÿ = Au \quad , \quad u = \begin{matrix} ÿ \\ ÿ \\ ÿ \end{matrix} \begin{matrix} x \\ y \\ z \end{matrix} \begin{matrix} ÿ \\ ÿ \\ ÿ \end{matrix} \,, A = \begin{matrix} ÿ \\ ÿ \\ ÿ \end{matrix} \begin{matrix} a & 0 ÿv \\ 0 ÿa & ÿv \\ ÿv & ÿv 0 \end{matrix} \begin{matrix} ÿ \\ ÿ \\ ÿ \end{matrix} \,, a = i, v = iF10/ . \qquad (4.66)$$

The equation has an exact solution, which, however, is not required. The resonance curve for forced quantum oscillations is well known (see Fig. 4.19). The population of the state ÿ, with the initial state ÿ, changes in a two-level system as

$$1 + \frac{^{2}}{4|ν|^{2}}^{-1} \sin 2 \, t \sqrt{\frac{^{2}}{4} + |ν|^{2}} \quad . \qquad (4.67)$$

It can be seen that the amplitude of changes reaches its maximum under the resonance condition, =0.

For a multi-level system of equidistant levels, resonance occurs simultaneously in each pair of adjacent levels. Depending on the initial conditions, the initially unoccupied upper levels gradually become populated, which corresponds to the pumping of energy by forced classical oscillations. The amplitude of the population oscillations of each level, averaged over a sufficiently large time interval, is also maximum in this case under resonance conditions, although the oscillations are not strictly periodic (with an infinite number of levels).

character.

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Therefore, we restrict ourselves to the case of exact resonance: =0 in (4.65). Then the value of a in the matrix A is equal to zero. The equations det(A ÿ ÿI)=0 and Aui = ÿiui,i =0, 1, 2 give the eigenvalues ÿ of the matrix A.

$$ÿ0 = 0 , ÿ1,2 = \pm v\ ÿ\ 2 \qquad (4.68)$$

and normalized eigenvectors

$$u0 = \frac{1}{ÿ2} \begin{pmatrix} ÿ \\ ÿ \\ 1\ 0 \\ ÿ \end{pmatrix}, \quad u1 = \frac{1}{ÿ2} \begin{pmatrix} ÿ1/ÿ\ 2 \\ ÿ \\ ÿ1/ÿ\ 2 \\ ÿ \\ 1 \\ ÿ \end{pmatrix}, \quad u2 = \frac{1}{ÿ2} \begin{pmatrix} ÿ \\ 1/ÿ2 \\ ÿ \\ 1/ÿ2 \\ ÿ \\ 1 \\ ÿ \end{pmatrix}.$$

The general solution of equation (4.66) is a combination of these vectors of the form

$$u = \sum_{i=0}^{2} diuieÿit .$$

Making the reverse substitutions, we obtain the coefficients ci (=0)

$$c1 = \frac{1}{ÿ2} \left(\frac{d1\ d2\ eÿ1t +}{eÿ2t\ ÿd0\ ÿ\ ÿ2\ ÿ2\ 1} \right), \qquad (4.69)$$

$$c0 = \frac{}{ÿ2} d1eÿ1t + d2eÿ2t ,$$

$$cÿ1 = \frac{1}{ÿ2} \left(\frac{d1\ d2\ eÿ1t +}{eÿ2t\ .\ d0\ ÿ\ ÿ2\ ÿ2} \right)$$

Let us assume that

at t = 0 the system was in the state m = 0, that is, |c0(0)| = 0. From here we find the coefficients ci(0) satisfying the conditions. In particular, d0 = 0, d1 = d2 = 1/ ÿ 2. Substituting this into the expressions for ci and taking into account that

$$ÿ1,2 = \pm iÿ \quad , \quad ÿ = \frac{F10}{ÿ\ 2} , \qquad (4.70)$$

we get

$$c0 = \cos ÿt \sin ÿt . , c1,ÿ1 = ÿ2 \frac{ÿi}{} \qquad (4.71)$$

In this case, the populations of states m = 0, m = ±1 oscillate accordingly as cos2 ÿt and $\frac{}{1\ 2}$ sin2 ÿt.

The notation of the wave function (4.57) implies that the probability density at the point ÿ0 is equal to

$$p(ÿ0,t) = ÿ(ÿ0,t)|ÿ(ÿ0,t)r,ÿ = \qquad (4.72)$$

$$= \sum_{\{i\}\{i\}} cÿ\ \{i\}(t)c\{i\}(t)ÿ\{i\}|ÿ\{i\}r,ÿ \exp[ÿi(ÿ\{i\}\ ÿ\ ÿ\{i\})t/] .$$

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The group of indices {i} consists of the radial k, azimuthal l and magnetic m quantum numbers:

$$ÿ\{i\} = Rkl(r)Ylm(ÿ, ÿ) ÿ Rkl(r)P|m| \quad l \quad (ÿ) \exp(imÿ) ,$$

see (4.4). The terms of the sum (4.72) with k = k and l = l oscillate rapidly, Therefore, we neglect their contribution. Here we will need a formula for spherical functions.

$$Ylm = ÿlm(ÿ) \exp(imÿ) \cdot \frac{1}{\sqrt{ÿ2ÿ}} \tag{4.73}$$

The functions ÿlm(ÿ) are normalized by the condition

$$ÿlm|ÿlm = \int_0^ÿ |ÿlm|^2 \sin ÿ \, dÿ = 1 .$$

They have the appearance [122]

$$ÿlm = (ÿ1)^{(m+|m|)/2} \, i^{|l|} \sqrt{\frac{2l+1}{2} \frac{(l ÿ |m|)!}{(l + |m|)!}} 1/2 \, P|m|_l (\cos ÿ) , |m|ÿ l, \tag{4.74}$$

Where

$$P^m_l(x) = (1 ÿ x2)^{m/2} \frac{dm}{dxm} Pl(x), \quad x = \cos ÿ, \quad m ÿ 0$$

— associated Legendre functions, and

$$Pl(x) = \frac{1}{2ll!} \frac{dl}{dxl}(x2 ÿ 1)l$$

— Legendre polynomials.

Taking into account the normalization of radial functions, the probability density is equal to

$$p(ÿ0,t) = \sum_{kl} pl(ÿ0,t) , pl(ÿ0,t) = \tag{4.75}$$

$$= \sum_{mm} cÿ \, lm(t) clm \, (t) ÿlm|ÿlm \exp[iÿ0m ÿ i(ÿm ÿ ÿm)t/] .$$

Summation over k is reduced to an unimportant constant coefficient and is omitted below. The functions ÿlm(ÿ) are generally not orthogonal at different m. Let us denote

$$amm = ÿlm|ÿlm , cmm = cÿ \, lmclm , \tag{4.76}$$

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and we take into account (see (4.3)) that

$$\ddot{y}m = \ddot{y}\ddot{y}mHz = \ddot{y} \quad \frac{q}{2McmHDC} = \ddot{y}\ddot{y}0m. \tag{4.77}$$

Then the probability density takes a convenient form

$$pl(\ddot{y}0,t)= \sum_{mm} amm\, cmm\,(t)\, \exp[im(\ddot{y}0 + \ddot{y}0t)] . \tag{4.78}$$

Recall that density (4.78) refers to a particle in superposition states of the Zeeman multiplet with a certain azimuthal number.

There are two contributions to the density (4.78), interference and non-interference. The latter, m = m , obviously, comes down to constant-the given value (amm = 1)

$$p = \sum_{m} ammcmm(t)= \sum_{m} cmm(t)= Const \quad ,$$

since the sum of the probabilities of the states of the multiplet is, by condition, invariable Menna.

We write the interference contribution as follows, by introducing For convenience, the notation $\ddot{y} = \ddot{y}0 + \ddot{y}0t$, and taking into account that $am,m\pm1 = \ddot{y}lm|\ddot{y}l,m\pm1 = 0$, $a\ddot{y}1,1 = \ddot{y}1$:

$$pl(\ddot{y}0,t)= a\ddot{y}1,1\, c\ddot{y}1,1e2i\ddot{y} + c.s. . \tag{4.79}$$

Substituting the values from (4.71) we find, accurate to within a coefficient,

$$pl(\ddot{y}0,t) = \sin2\, \ddot{y}t \cos(2\ddot{y})\, \ddot{y}\, (1 \ddot{y} \cos 2\ddot{y}t) \cos 2(\ddot{y}0 + \ddot{y}0t) . \tag{4.80}$$

We then proceed as in section (4.1). First, we find the moving average of the probability density over the interval $[\ddot{y}T,T]$. Then we average the square of the obtained value. The result will be the magneto-dependent part of the probability of dissociation of the ion-protein complex in perpendicular, constant and alternating, magnetic fields. It can be shown that moving average leads to the following estimate

$$T\,[pl(\ddot{y}0,t)] = 2 \quad \frac{1}{-} \int_{t\ddot{y}T}^{t+T} pl(\ddot{y}0,t\,)\, dt\, \ddot{y}$$

$$\ddot{y} \cos 2(\ddot{y}0 + \ddot{y}0t) \quad \frac{\sin 2\ddot{y}0T}{2\ddot{y}0T} \cdot \frac{1}{2} \cos 2\ddot{y}0 \cos 2\ddot{y}t \quad \frac{\sin 2kT}{2kT} ,$$

$$\ddot{y} = \ddot{y} \pm \ddot{y}0 .$$

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The square of this quantity is reduced to the sum of the squares of its two terms, so as the main contribution, depending on magnetic conditions, is created any one of the terms. Averaging T 2[pl(ÿ0,t)], we take into account the relationship nia

$$\overline{\cos 2\ddot{y}t} = 1/2 , \qquad \overline{\cos 2\,2\ddot{y}0} = 1/2 ,$$

where averaging is carried out respectively over an infinite time interval and over a uniformly distributed random variable ÿ0 ÿ [0, 2ÿ). We finally obtain

$$P\ddot{y} \quad \frac{\sin 2\,2\ddot{y}0T}{(2\ddot{y}0T)2} \quad \frac{1}{-}\,\frac{\sin 2\,2kT}{(2kT)2\,8} \;,\ddot{y} = \ddot{y} \pm \ddot{y}0 \,.+ \qquad (4.81)$$

Thus, in perpendicular fields there is also an effect magnetosensitive dissociation due to interference of quantum states of the ion. The first term (4.81) describes the increase in the probability of dissociation in a zero constant field, that is, at ÿ0 ÿ 0. It is interesting that this also occurs in the presence of an alternating magnetic field, in contrast to an ionic one interference in parallel fields.

The second term (4.81) is associated with the action of an alternating magnetic field perpendicular to the constant one. In contrast to interference in parallel fields, the factor sin x/ x now determines the amplitude, not the frequency spectrum. The selection rules following from the form of the operator of interaction of a perpendicular alternating magnetic field with an ion remain only transitions with m = ±1. Therefore, the frequency spectrum, as follows from (4.65), (4.77) in this case consists of a single maximum at

$$\ddot{y}peak = \ddot{y}\ddot{y}0 \quad , \qquad (4.82)$$

the form of which follows from the relation (4.67).

The amplitude spectrum of dissociation follows from the relation ÿ = ÿ± ÿ0 =0, ÿ = ÿ2F10/ or

$$F10 = \pm\ddot{y}0/\ddot{y}\,2 \,. \qquad (4.83)$$

Using (4.64), after simple transformations we obtain a formula for the relative amplitude (calculated by modulus) of a variable MP at which maximum response is possible:

$$h = \frac{HAC}{HDC} = \frac{\ddot{y}1}{\ddot{y}0} = \sqrt{\frac{2}{l(l+1)}} \,. \qquad (4.84)$$

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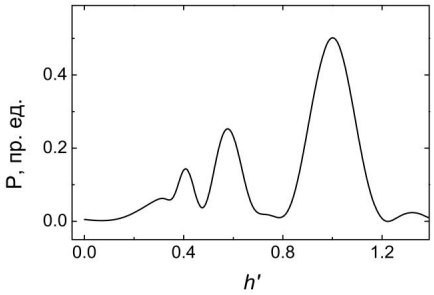


Fig. 4.20: Amplitude spectrum dissociation in perpendicular MP. The width of the peaks is determined parameter ÿ=ÿcT, calculation for Ca2+ at HDC = 45 ÿT, T = 0.07 sec.

In particular, with resonant interference of levels l = 1 we obtain

$$h_{peak}{}^{=1} \quad ,$$

which is very different from the value h = 1.8 for the position of the first spectral peak in amplitude in parallel MFs, Fig. 4.28. In addition, h = 1 is not the minimum value for observing resonant interference in perpendicular fields. Indeed,
interference in the Zeeman levels of groups l = 2, 3, 4, 5.. occurs independently and the corresponding amplitudes of the maximum effective MPs are 0.58, 0.41, 0.32, 0.26, etc. The relative contribution of these groups the overall effect will be determined by the populations of the l-states. In this In this connection, we note the following.

The given dependencies are valid for a three-level system, l = 1. When the Zeeman multiplets next in azimuthal number l are populated, resonant transitions occur simultaneously for all adjacent pairs of levels, even if initially only levels m = 0, ±1 are populated, since all levels are equidistant.

over time, the population of levels m = 0, ±1, which determine resonant interference, will decrease due to transitions to higher angular modes. Generally speaking, this reduces the relative amplitude interference maxima of states l> 1. Therefore, observation interference of bound ions in perpendicular fields to a greater extent degree than in parallel ones, depends on the implementation of specific initial conditions, when only a small number of Zeeman sublevels are populated.

It is important that only that multiplet exhibits resonant interference for which the condition of the effective amplitude of the magnetic field is satisfied, in this case, interference effects arise independently for each of the multiplets. Then, on the basis of (4.81), (4.75), (4.70), (4.64) it is possible

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but write down

$$P \ddot{y} \quad al \frac{\sin^2 2\ddot{y}lT}{(2\ddot{y}lT)^2}, \qquad (4.85)$$

$$2\ddot{y}lT = \frac{F10}{\ddot{y}\,2+\ddot{y}0\,2T = 1\ddot{y}\,h} \sqrt{l(l+1)\,2}\ \ddot{y}\,.$$

The amplitude spectrum calculated by this formula, with a decrease in the relative interference amplitudes with increasing l according to al ÿ 2ÿl, is shown in Fig. 4.20. In a more general case, when in the linear combination (4.69) the coefficients d are arbitrary (but still , By-satisfy the normalization condition

di = 1), another expression should be written for cÿ1,1, see (4.79), dÿ i

$$c\ddot{y}1,1 = D0 + iD1\sin(\ddot{y}t + \ddot{y}1) + iD2\sin(\ddot{y}t + \ddot{y}2) + D3\cos(2\ddot{y}t + \ddot{y}3), \qquad (4.86)$$

Where

$$D0 = \ddot{y}d\ddot{y}\,0d0/2+(d\ddot{y}\,1d1 + d\ddot{y}\,2d2)/4,\ D1 = \ddot{y}\,\ddot{y}\,2|$$
$$d0d\ddot{y}\,1|/2,\ddot{y}1 = \ddot{y}\,\overline{\arg}\{d0d\ddot{y}\,1\},\ D2 = \ddot{y}\,\ddot{y}\,2|d0d\ddot{y}\,2|/2,\ddot{y}1 =$$
$$\arg\{d0d\ddot{y}\,2\},\ D3 = \ddot{y}|d\ddot{y}\,1d2|/2,\ddot{y}3 = \ddot{y}\,\arg\{d\ddot{y}\,1d2\}.$$

It can be shown that the phase shifts ÿi are unimportant for calculating P. New, compared to (4.80), after substituting cÿ1,1 into (4.79), is the term pl(ÿ0,t), proportional to

$$\ddot{y}\sin(\ddot{y}t)\sin 2(\ddot{y}0 + \ddot{y}0t).$$

It results in the appearance of an additional term in P

$$\ddot{y} \quad \frac{\sin^2 2\ddot{y}T),\ddot{y}}{} = \ddot{y}/2 \pm \ddot{y}0\,(2\ddot{y}T)^2 \quad ,$$

which gives interference peaks at ÿ = 0. Then, in addition to (4.84), we have an additional relation for the possible effective ampli-

there

$$h = 2\sqrt{\frac{2}{l(l+1)}}.$$

Thus, in the general case, the amplitude spectrum of interference in a perpendicular magnetic field is a superposition of the spectrum of Fig. 4.20 and the same

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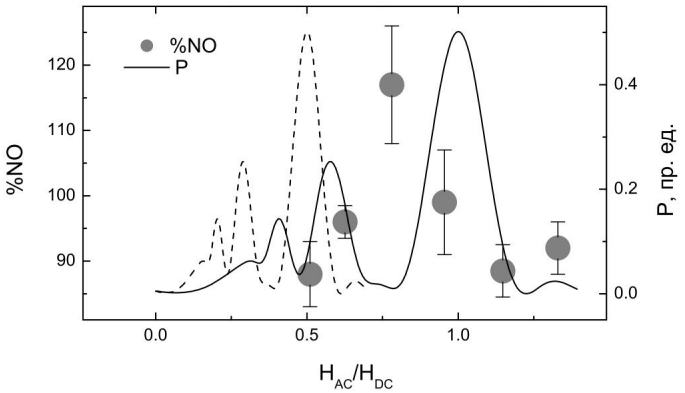


Fig. 4.21: Components of the amplitude spectrum of ion-protein dissociation and data [387] on MBE on PC-12 cells in constant and perpendicular linearly polarized alternating magnetic fields.

spectrum stretched twice along the h-axis . Therefore, in contrast to interference in parallel fields, not only the relative height, but the position of the spectral maxima of the superposition also depends on the initial conditions of the ion in the capsule. Under conditions of a priori uncertainty of the initial conditions, one would expect a complex and poorly reproducible amplitude spectrum, occupying the range h ÿ 0.2–2.2.

Note that the amplitude spectra considered are valid for a circularly polarized alternating magnetic field. With linear polarization, only one of the circular components is effective, the amplitude of which is two times smaller than the amplitude of the linearly polarized called field.

Garcia-Sancho, Montero et al. [398] observed 16% MBE in the first pendicular orientation of magnetic fields

b(141)Bp(41)f(14.5)n(8)C(100 ± 34.2)MBE(116 ± 6.7)P(< 0.001) .

Here C is the control level, MBE is the level in the MP, P is the probability of making a mistake by rejecting the null hypothesis. The relative amplitude, taking into account the effectiveness of one circular component, was h = 1.72. The frequency used in this constant MF is close to Larmor frequency of calcium ions, 15.7 Hz, and sodium, 13.7 Hz. Although the effect was observed by the capture of the 42K label, it can be assumed that this The process was controlled by some Ca-binding protein.

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Blackman, Blanchard et al. [387] measured using the method described in section 2.3 the relative number of nerve cells with processes neurites that appeared as a result of exposure of the cell culture to perpendicular to the MP. Experimental formula

b(18.7–48.6)Bp(36.6)B(< 0.28)f(45)

allowed us to determine the section of the amplitude spectrum of the MBE. These data, reduced to the dimensionless variable HAC/HDC, together with the two specified components of the theoretical amplitude spectrum, adapted to the case of linear, as in the experiment, polarization of the magnetic field, are presented in Fig. 4.21. Taking into account the uncertainty of the relative weights of components and the probable presence of factors broadening spectral peaks, the agreement between theory and experiment could be assessed as satisfactory: it is already good that the positions of the maximum effect in both physical theory and biological experiment coincide in order of magnitude. The system used in the experiment

The frequency of 45 Hz is close to the Larmor frequency of lithium ions in this constant field, 40.5 Hz. Unfortunately, the frequency is not given in [387] MBE spectrum. The interference mechanism predicts quite a large peak width P in frequency under such conditions, which would be easy to establish experimentally. The peak shape is given by the envelope (4.67), (1 + 2/4|ν| 2)ÿ1. From this it can be seen that the width at half maximum of the peak is equal to 4|ν| or 4|F10|/. Since (4.83) gives |F10| = ÿ0/ ÿ2 at effective amplitudes, the peak width in frequency will be f = ÿ 2ÿc or

f = ÿ2.

Senkevich, Haylock and others in the work [226] studied in a special method of learning ability of mice when irradiated with perpendicular magnetic fields of varying intensity according to the formula

b(0, 7.5, 75, 750, 7500)Bp(40)f(50) .

After training and irradiation, the mice made mistakes. In each of Over the next ten days, the mice were tested for errors in performing test. The author of the book conducted his own analysis of the data. At first and at tenth day after irradiation the difference between differently irradiated and was absent in control mice. Days from 2 were taken for analysis. 9 for which the results were averaged. The measured value in the experiment was the relative error level L in % for all experimental lines, control and with different exposures. The relative magnitude of errors was calculated as (Lcontr ÿ Lexp)/Lcontr

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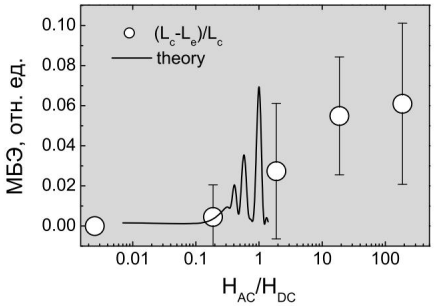


Fig. 4.22: Adapted data [226] for MBE in mice in perpendicular to the MP. Line a typical theoretical crite-Vaya.

and is presented as a function of the intensity of the alternating magnetic field. These data are shown in Fig. 4.22 together with a typical theoretical curve for case of perpendicular fields. It is evident that in the region of large amplitudes there is a complete discrepancy, since the theory predicts a decrease in the interference effect. This is probably due to the inclusion of other mechanisms, since the field intensity of 750 ÿT at this frequency already exceeds the accepted limits of safe radiation exposure. It should be noted that that the frequency f = 50 Hz in a constant MF of 40 ÿT is close to the Larmor frequency the frequency of lithium ions 7Li equal to 43.7 Hz and 6Li - 51 Hz.

Let us note an important feature: *the relative width of the peak at interference in perpendicular MPs is relatively large and does not depend on the type of ion involved in magnetoreception, nor from the constant of its binding to the protein.*

4.4.2 Interference with inclined orientation lei

The inclined orientation of the constant and alternating magnetic fields, as was said, is reduced to the simultaneous action of the parallel and perpendicular components of the alternating component. In this case, two situations.

The frequency of the magnetic field is different from the Larmor frequency

MP with a frequency different from ÿ0 can cause a significant increase the probability of dissociation of the ion-protein complex in parallel orientation, Fig. 4.8. At the same time, with perpendicular orientation, the MF frequency does not correspond to the frequency of Zeeman transitions (ÿ0), therefore resonant interference does not occur. This means that the response to the MF can only be formed by the interference mechanism.

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resonances in parallel fields. The presence of a magnetic field component perpendicular to the constant field does not affect the formation of the response to the parallel component. It is important that this conclusion, taking into account the large resonance width, is valid when the excitation frequency is separated from the Larmor frequency by a sufficiently large amount, by ÿ ÿc.
Otherwise, a situation similar to the following arises.

The frequency of the magnetic field is equal to the frequency of magnetic resonance.

In this case, transitions occur that change the populations of quantum states. The formation of responses is not independent. It is logical to expect, due to the structure of dynamic equations for coefficients of type (4.58), that the simultaneous action of parallel and perpendicular components will violate the specific interference conditions
for each of the mechanisms. As a result, an increase in the probability of magnetosensitive dissociation will not be observed, even if the parameters of the parallel or perpendicular components of the alternating magnetic field correspond to the response maxima conditions found above.

This general statement does not exclude the possibility of an interference burst with some unique combinations of fields, frequencies
and angles. However, their calculation and experimental verification are hardly advisable, since they do not add to knowledge about the nature of the phenomenon. Strictly parallel or perpendicular combinations of fields would be self-sufficient from the point of view of studying the interference effects of dis-
sociations.

4.5 Rotations of the ion-protein complex in magnetic field

Many biochemical reactions occur not on the surface of cell membranes and associated structures, but in the cytoplasm or attached to organelles that rotate during life.

For example, the hairs of the flagellar motor of some intestinal cells
the sticks rotate at a speed of about 300 rpm, so the body
The bacteria rotates in the opposite direction at a rate of several revolutions per second. The enzyme ATPase rotates during operation,
some enzymes attached to DNA-RNA in the process of nucleosynthesis, etc., references can be found in the work of the author, Alipov and Belyaev
[303] In this case, as suggested in the author's work [295], it is advisable to take into account one's own molecular, as well as macroscopic,

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together with the biological system, the rotation of macromolecules containing
connecting cavities.

4.5.1 Molecular rotations in MP: amplitude spectrum

Let the ion be bound to a protein rotating with an angular velocity ÿ. In the general case, the direction of rotation does not coincide with the direction of the magnetic field. Let's direct the z-axis along the rotation axis and go into rotation with protein coordinate system, Fig. 4.23.

In this coordinate system, the constant magnetic field is equal to HDC cos ÿ, and the coaxial variable magnetic field is reduced to HAC cos ÿ cos(ÿt), and the relative amplitude h retains its previous value regardless of angle ÿ between the directions of rotation and the MP. This means that only the cyclotron frequency changes with angle ÿ: ÿc = qHDC cos ÿ/M c, so that some frequency of the magnetic field ÿ, effective in the case ÿ = 0, becomes ineffective with increasing ÿ.

The estimate of the range ÿ within which a given frequency ÿ is still effective is based on the ratio of the relative widths of the peaks P: f = ÿ/nÿ, see (4.27). Relative decrease in cyclotron frequency due to axial deviation must be less than half-width peaks:

$$1 \ddot{y} \cos \ddot{y} < \ddot{y}/2n\ddot{y} .$$

This determines the limiting angle ÿ ÿ 23o for the Ca-protein complex (ÿ ÿ 20 at HDC = 40 ÿT). From this it is easy to obtain that the relative amount of randomly rotating ion-protein molecules that could form a given spectral peak in the response is equal to 1 ÿ cos ÿ. This amount is about 5–10% and increases with decreasing HDC.

In a rotating frame of reference, a perpendicular rotating component of the magnetic field arises. This component causes resonant transitions in a wide, ÿ ÿc, frequency range centered on the Larmor frequency, provided that the relative amplitude of the component h_{perp} of the order of unity (see section 4.4).

Such transitions destroy the constructive interference that leads to pronounced P peaks, or rather, it does not arise under such conditions. Therefore, only those molecules that rotate coaxially with the magnetic field, react to MP exposure. The relative number of potentially reactive molecules should also be estimated from this limitation.

It turns out to be stronger. At amplitudes h_{perp} ÿ 0.1, response

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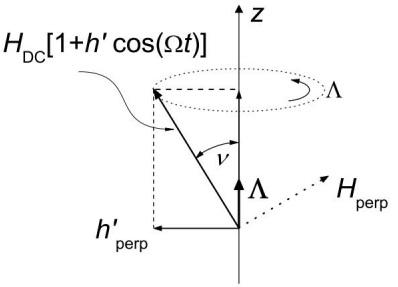


Fig. 4.23: Projections of uniaxial MP in a rotating system of co-ordinate.

on a perpendicular alternating magnetic field the frequency is significantly narrowed and does not cause any effects, except in the relatively rare situation when the angular velocity ÿk is equal to the Larmor frequency. From Fig. 4.23 it follows that the value of h_{perp} ÿ 0.1 defines ÿ ÿ 6o and less, but all another significant amount, ÿ 1%, of reacting ion-protein molecules cool

In the case of an additional constant magnetic field Hperp, perpendicular to the initial field, HDC(1+h cos ÿt), there are changes in rotating coordinate system. MP Hperp cos ÿ is added to h perp, which obviously has no consequences. A small value of Hperp sin ÿ is added to the uniaxial field: HDC cos ÿ(1 + h cos ÿt)+ Hperp sin ÿ, thus determining the effective cyclotron frequency ÿ˜ c equal-nuyu

$$ÿ˜ c = ÿc \cos ÿ + \frac{Hperp}{HDC} \sin ÿ .$$

It follows that the perpendicular component in a fixed coordinate system, Hperp, can be several times greater than the constant component of the uniaxial magnetic field without noticeable changes in position, and consequently in the magnitude of the effect on rotating complexes. This phenomenon is completely impossible for stationary complexes, since they do not have an "instrument" similar to the axis rotation to register the difference between the MP components. Fixed complexes respond to the absolute value of the static MP (H2 DC + H2 perp)1/2, and not into its components.

A special experimental study [277] of the narrow spectral peak of MBE on the *E. coli* cell culture in a combined MP H(43.6)Hp(0–147)h(30)f(9), in the presence of a variable perpendicular component of 0–147 ÿT, did not reveal any changes.

Rotating ion-protein complexes are likely involved in magnetic

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toreception under these conditions.

In general, the asymmetric (red shift) broadening of frequency spectral peaks arises due to the random orientation of the molecular rotation axes. However, we will not complicate the formulas by averaging over the angle ÿ: this would not lead to qualitatively new effects. Taking into account the more or less significant part of randomly rotating molecules contributing to the P-response at a given effective frequency, we consider the case ÿ = 0, that is, molecules rotating coaxially with a uniaxial magnetic field. In this case, the coordinates of the initial reference frame r, ÿ, ÿ and the rotating frame r , ÿ , ÿ are related by the simple relation: r = r ÿ = ÿ ,

ÿ = ÿ + ÿt. The operators included in Hamiltonian (4.1) are not changed by this transformation, since the derivatives with respect to the polar angle are equal in both , systems: ÿ/ÿÿ = ÿ/ÿÿ . Therefore, all relations, with the exception of those containing ÿ, remain valid in the rotating system. Thus, the transition to the rotating system is accomplished simply by substituting ÿ + ÿt for ÿ. It follows that the angular coordinate of the gate of a protein rotating with an angular velocity from the discrete series ÿk is equal to

ÿ0 +ÿkt.

Obviously, the probability density of an ion in a rotating protein can be obtained from (4.8) by substituting ÿ0 ÿ ÿ0 +ÿk. Therefore, the dissociation probability follows from (4.23) after this substitution.

$$P = \sum_{mmnk} |amm \mid 2|ck|\, 2\, \frac{\sin 2A}{A2}\, J2_n \quad \frac{m}{2}\,\frac{h}{f} \quad , \qquad (4.87)$$

$$A = m \quad \frac{ÿ0 + ÿk\ ÿc}{} \quad + nf\ ÿ \quad ,$$

where $|\hat{c}k|^2$ are the statistical weights of rotational states. The case of various ion-protein complexes with quantized rotations in a constant magnetic field is considered in the work of the author, Alipov, and Belyaev [303].

In order to show the changes in the amplitude spectrum P in a uniaxial magnetic field, it is sufficient to consider them for any one velocity ÿ. The positions of the frequency spectral peaks P are given by the equation A = 0, which leads to the relation

$$f_{max} = ÿm(1 + 2ÿ)/2n,$$

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where ÿ = ÿ/ÿc is the relative velocity of molecular rotation. It is important that the relative frequencies of the maxima P depend on the angular velocity. The main contribution to the sum (4.87), up to

80–90%, is made by terms with n = ±1. For the analysis, due to the equality J2 1(x)=J2 ÿ1(x), it does not matter which case to choose—we will take n = 1. Accordingly, the contribution is maximum at

$$f_{max} = ÿm(1 + 2ÿ)/2 , \quad (4.88)$$

and any of these members has the form

$$J2_1 \frac{h}{1 + 2ÿ} , \quad (4.89)$$

which follows from equation (4.87). Let us find the conditions under which the amplitude spectrum has the functional motive J2 1(ÿh), where ÿ is a certain coefficient (not to be confused with ÿ in (4.10)). This makes sense, since experimental spectra approximated by the function J2 1(2h) are known. The value ÿ = ÿ2 is also suitable, due to the equality J2 1(ÿx)=J2 1(x). It is easy to find from (4.88), (4.89) that the value ÿ determines the relative frequency of rotation of the complex and the frequency of the magnetic field, under which the amplitude spectrum will have the specified form J2 1(ÿh):

$$ÿ = ÿ 1 ÿ ÿÿ1 /2 , f = ÿ = ÿm/2ÿ. \quad (4.90)$$

In general, the shape of the amplitude spectrum of a rotating complex depends on the type of bound ion; the coefficient in the Bessel function argument can take on different values. Accordingly, the first response maximum can be achieved even at values of h smaller than 1.8. As can be seen, the positions of the spectral peaks in the MF amplitude

vary quite a lot depending on the speed of rotation of the com-
plex.

In the particular case when the natural angular velocity of the complex corresponds to the parameters of the ion and the constant field, and the field frequency f = 1/2, that is,

$$ÿ = ÿ1/2 ± 1/4 , f = 1 + 2ÿ = ±1/2 , \quad (4.91)$$

then the amplitude spectrum has the indicated form J2 1(2h), maximum at h ÿ 0.9. It is interesting that the magnetic conditions used in [421, 488], where just such a spectrum was observed, almost exactly satisfy these rules, if we assume that lithium- or magnesium-protein rotating complexes are involved in magnetoreception. Detailed

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analysis of the correspondence between experimental data and theoretical predictions for rotating complexes is given in section 4.9, see also the work author [300].

Note that the indicated amplitude spectrum is not a consequence of the shift of the peaks of the usual J2 n(h) spectrum to smaller amplitudes at molecular rotation. This spectrum gradually disappears as a whole when the angular velocity or frequency of the magnetic field deviates from their optimal values values.

■ It is interesting that equations (4.90) predict the conditions for the sensitivity of the system to ultraweak MFs. Indeed, for sufficiently for large values of ÿ 1 the first maximum of the response occurs in an alternating field with amplitude ÿ HDC/ÿ. According to equations (4.90) the field frequency must also be small: f ÿ fc/ÿ, and the constant MF selected so that the Larmor frequency coincides with the natural frequency of rotation of the complex. This exactly corresponds to the implementation magnetic vacuum conditions for non-rotating complexes. The factor limiting the sensitivity in this case is time lifetimes of angular modes of quantum states ÿL : the performance of the mechanism is limited from below by MF frequencies of the order of 1/ÿL . Experimental evidence of biological sensitivity to ultraweak MFs There are, but unfortunately, the amplitude spectra have not been measured and a comparative analysis is impossible. Also unknown, from those not related to magnetobiology experiments, long-lived molecular quantum states at room temperature. Note that those states The ion species in the protein cavity, whose lifetime is postulated in this book to be at least 0.1 s, are hypothetical. Their nature is also unknown, but their introduction is justified by the high level of agreement between calculated and experimental data. Interestingly, however, designs such as a molecular gyroscope (see Section 5.4) could provide the lifetimes required to detect ultraweak magnetic fields.

4.5.2 Macroscopic rotation: spectrum shift along frequency

The rotation of ion-protein complexes, which changes the positions of spectral peaks in frequency in accordance with (4.88), can also be considered and macroscopic rotation. The latter means rotation together with the entire biological system or sample, which is placed, for example, on a rotating platform. The notation ÿ is used for angular velocity of macroscopic rotation, the designation ÿ is conserved

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is due to microscopic molecular rotation. Macroscopic rotation at an arbitrarily large angle to the direction of a uniaxial magnetic field will destroy constructive interference by
for the same reasons as in the case of molecular rotations. Therefore, let us assume, as before, that the macroscopic rotation is coaxial with the magnetic field. In this In this section, without loss of generality, we assume molecular rotations absent, that is, ÿ=0:

$$f_{max} = ÿm(1 + 2ÿ)/2n.$$

where ÿ = ÿ/ÿc. The peak shift for a given value of ÿ is mÿ /n.
The shift will be allowed if it exceeds the peak half-width in absolute value. The argument of the sin2 A/ A2 multiplier in (4.87), that is,

$$A = [m(1/2+ÿ) + nf]ÿ,$$

determines the width of the peaks. Taking into account that the value of A ÿ ÿ corresponds to the width of the function sin2 A/ A2 at its half-height and using the ratio f ÿA/ÿf ÿ ÿ, we can find the peak width f ÿ ÿ/nÿ,
(4.27). Therefore, to resolve the shift, the inequality mÿ > ÿ/2ÿ must be satisfied. The most pronounced peak comes from the interference of quantum angular modes with the difference in magnetic quantum numbers m = 2, and in any case m ÿ 1. Then we have a prime
the ratio that determines the minimum speed of macroscopic rotation for observing the shift of spectral peaks: ÿ > ÿ/2ÿ.
In absolute terms this ratio is:

$$ÿ > ÿ/2T. \qquad (4.92)$$

As already mentioned, a good agreement between the experimental and calculated frequency spectra for calcium and magnesium ions is achieved at T = 0.05–0.1 s. In this case, observation of the shift is guaranteed if the rotation speed, ÿ/2ÿ, is only 1.5–2 revolutions per second.
or more. Fig. 4.24 shows the results of calculations of P with an angular velocity of ÿ=0.1ÿc. The direction of rotation with respect to the MP determines where the peaks shift, towards larger or smaller ones
frequencies.

The effect of shifting the spectral extrema of the MBE during rotation of the biosystem is one of the significant and verifiable
predictions of the mechanism of interference of bound ions [295].

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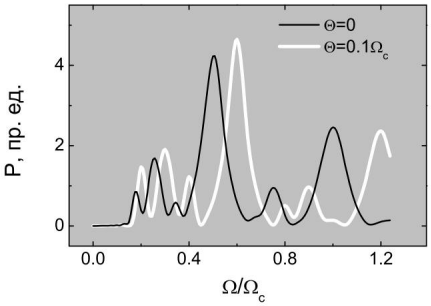


Fig. 4.24: Shift of the dissociation probability maxima P by frequency during rotation of the ion-protein complex in uniaxial MP with angular frequency ÿ = 0.1.

4.5.3 Rotation in constant magnetic field: decay of the effect left field

Let the ion-protein complex be in a state with a discrete series of molecular rotations ÿk = kÿ. This allows us to describe both a quantum top and a classical rotator in the following situation. Different molecules of the same ion-protein complex can be attached to relatively stationary (k = 0) carriers of the type biological membranes, as well as rotating ones, such as DNA. Then the sign projection of the angular velocity onto the direction of the magnetic field determines the magnitude k = ±1. Under the condition HAC = 0, all Bessel functions except J0(0) = 1 drop out of the sum (4.87). This gives a single value n = 0 in (4.87). Then the dissociation formula in a constant magnetic field takes the following form:

$$P = \sum_{mmk} |amm|\, 2|ck|\, 2\,\frac{\sin^2 A}{A^2}\, m\,(ÿ0 + ÿk + ÿ)\, T. \quad (4.93)$$

Note that the factor sin2 A/A2 now determines the dependence of P on the magnitude of the magnetic field, and not on the field frequency. The formula predicts the maximum effect at A = 0, or at ÿ0 = ÿÿk ÿ ÿ, which gives an expression for values of constant MP that provide the maximum probability dissociation:

$$(HDC)max = (kÿ\frac{-1}{b} + ÿ)\,, \quad (4.94)$$

where b = q/2Mc is proportional to the ratio of the charge to the mass of the ion. For ion-proteins, which do not rotate by themselves, k = 0, there is the only maximum of P at the field strength HDC = ÿÿ/b. If there is no macroscopic rotation, then this peak appears at HDC = 0, which is associated with the so-called bio-

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logical effect of magnetic vacuum. In addition to this maximum, additional peaks may appear due to proper rotation
complex in accordance with (4.94). Such extrema are considered in the work of the author, Alipov and Belyaev [303] in relation to the polyextremal dependence of MBE on constant MP in *E. coli* cells in the range of 0–110 ÿT [277].

Here we are investigating fixed complexes, k = 0. If the constant magnetic field is small enough, all types of ions that could interfere constructively under some other conditions, specific to each type of ion, exhibit such interference simultaneously. This
one of the possible reasons for the biological effects of magnetic vacuum. Indeed, the maximum P at HDC = 0 does not depend on the parameters Jonah.

Observation of extreme MBE dependencies in constant or uniaxial MP is often due to a lucky coincidence of circumstances: we need to guess what type of ions are involved in magnetoreception and select agreed parameters of the magnetic vacuum. On the contrary, biological effects of magnetic vacuum have been observed for many biological systems, see, for example, [377, 341, 502, 105, 179, 275]. This indirectly confirms the involvement of many types of ions in the magnetic vacuum effect.

Moreover, rotation in zero magnetic field affects all ions of these types, and not just the above-mentioned 1% of them, due to the absence of a distinct magnetic field direction. Apparently, the effect in this case should be most significant. Macroscopic rotation in a magnetic vacuum is a general method for testing the predictions of the interference mechanisms of the MBE. In a small magnetic field, the position of the peak associated with a fixed complex is determined by the relation

$$(HDC)max = ÿÿ/b . \qquad (4.95)$$

The position depends on the angular velocity. It is easy to find that the shift will be allowed under the same condition (4.92). That is, for calcium- and magnesium-protein complexes 1.5–2 rev/s. *The effect of the shift of the MBE extrema in a constant magnetic field during rotation of the biosystem* means decreasing effect at HDC = 0, Fig. 4.25.

In the absence of magnetic field, P is determined by the argument A = mÿT . In the absence of rotation, the argument is A = mÿ0T . It follows that
equal effects occur when ÿ0 =ÿ or

$$HDC = ÿ/b .$$

The last relation is close in form to (4.95), but has a different physical meaning. *Constant magnetic field and macroscopic rotation of the ex-*

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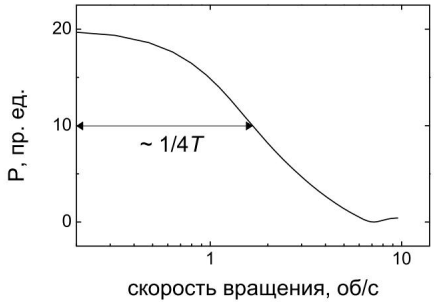


Fig. 4.25: Reduction of the magnetic vacuum effect with increasing rotation speed of the Ca-protein complex, formula (4.93), k =0.

are equivalent in their effects on fixed ion-protein complexes when they act separately. Equivalence can be established relative to a control level of effect common to both variables, that is, to the effect at HDC = 0, ÿ = 0.

■ Thus, the amplitude spectra of the dissociation of ion-protein complexes with intrinsic molecular rotation differ from the spectra for relatively immobile complexes. They are close in shape to J2 1(ÿh), where the coefficient ÿ is determined by the rotation rate. Probably, in living organisms, various

conditions for the functioning of metalloproteins are realized, including their rotational states. In [421], the first extremum of the amplitude spectrum was observed at h ÿ 0.9, and not at h ÿ 1.8, as predicted by the model for immobile molecules. This gave rise to a discussion [528], where the authors suggested errors and artifacts in the work of their opponents. It should be noted that the different amplitude spectra were obtained on different biological models, so it is logical to assume that in [421], the MBE associated with the dissociation of rotating complexes was measured. In [615], the amplitude spectrum also has a pronounced first maximum at h ÿ 0.5, Fig. 4.39. The first maximum at the frequency ÿc of the H+ ion was observed in [551] at h ÿ 0.6–0.7, and in [465] at h ÿ 1.4. In [374], the amplitude spectrum of [551] was confirmed, see Fig. 2.23 and Fig. 2.24. Apparently, groups of proton-binding sites are located on macromolecules that have their own or forced, as in the case of DNA-RNA synthesis processes, rotation. Then the amplitude spectra of [551, 374] can be approximated by ion interference functions, see Section 4.9. The component of the constant field perpendicular to the alternating magnetic field, in the case of using inclined fields, does not affect the position and

magnitude of the frequency maxima P on rotating complexes. This

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corresponds to observations [564, 277]. At the same time, fixed
the complexes are sensitive to the absolute value of the constant magnetic field, and, therefore, to each of its components.

Often experimental spectra are so complex that it is difficult to explain them without targeted testing of predictions.
within the framework of a model of any specific mechanism of the MBE. An experiment with biological samples on a slowly rotating platform in a constant or uniaxial magnetic field can confirm or
disprove theoretical predictions. Rotation in a uniaxial magnetic field predicts the shift of the MBE peaks in frequency. Rotation in constant
the field predicts a decrease in the effect of magnetic vacuum, regardless of the type of ions involved in magnetoreception, or a shift
peaks of the MBE on the field strength, if the complexes also have their own molecular rotation. The rotation of biological samples in itself, due to the action of centripetal accelerations, is capable of causing a biological reaction, and therefore requires special
control.

■ Two assumptions underlie the predictions of the ion interference mechanism for rotating complexes: 1) a sufficiently long lifetime of the quantum states of the ion, more precisely, only the angular modes of these states, and 2) the presence of dedicated sites in the binding
cavities where the ion yield is a nonlinear function of the ion probability density. For the observability of interference effects, these assumptions must be satisfied simultaneously. Therefore, it is unlikely that such predictions could be obtained within the framework of
any other theory. This means that testing and confirming the equivalence between a static magnetic field and macroscopic rotation with respect to a system initially placed in magnetic vacuum conditions would be direct evidence of the involvement of interference in magnetoreception. This is important because such evidence refines the search for possible solutions to the "problem"
kT ». Now it would be necessary to answer the question: why does the model of long-lived states described by the eigenfunctions of the central or axial potential approximate the true ones so well?
quantum states in a binding cavity perturbed by thermal fluctuations. This question, in contrast to the "kT problem" itself,
itself, does not have a hint of paradox.

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4.6 Influence of electric field on ion interference

Low-frequency electric fields (EF), like low-frequency MF,
do not cause any significant redistribution of populations due to transitions with changes in radial or azimuthal quantum numbers. The characteristic frequencies of these transitions are approximately 10 orders of magnitude higher than the frequency range under study. Therefore, as in the previous sections, it makes sense to consider

processes within individual Zeeman multiplets.

As already mentioned in section 1.4.3, relatively small electric fields, ÿ 10–100 V/m, are capable of quadratic the Stark effect can significantly change the energy levels. The changes are of the same order as the Zeeman splitting. Obviously, this is not may affect interference effects in parallel MPs, However, resonant interference in perpendicular fields is destroyed, since the frequency of transitions changes. In addition, EPs can be and an independent factor of ionic interference.

4.6.1 Interference of ions in alternating electric current sk field

The point is that the variable inhomogeneous EP causes both phase shifts and transitions in the Zeeman sublevels and at some conditions leads to an interference effect.

Let us select among all the indices i, numbering the wave functions central potential ÿi, i = {klm}, the group p related to the functions of some degenerate level with energy ÿp, and the group p of q indices of all other functions. In a homogeneous EP, degeneracy is partially is removed and the wave functions of each of the sublevels of the group p are written as follows [7]:

$$\ddot{y}_p = \ddot{y}p + \sum_q \frac{Vqp}{\ddot{y}p - \ddot{y}q}\ddot{y}q .$$

Since the indices p, q differ by at least one of the indices of the radial and azimuthal numbers, then the corrections to the wave functions are very small, of the order of Vqp/(ÿp ÿ ÿq) 1. Obviously, the interference effects dependent on the electric field will be of the same order of smallness and are of no interest. A different situation occurs in non-uniform EP.

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Let us calculate the matrix elements of the interaction operator of the electric field E with the dipole moment of the particle d = qr

$$V = \ddot{y}qrE .$$

Let us note immediately that all states of a single Zeeman multiplet have the same parity $(\ddot{y}1)^l$, that is, they either change or do not change sign upon coordinate inversion. In a homogeneous EP, the matrix elements of the operator V are proportional to the matrix elements of the vector r in
states of the same parity and are therefore equal to zero [122]. Non-zero elements can appear either due to interaction with the quadrupole moment or in an inhomogeneous EP. In the latter case, the field
can be represented by a Taylor series around the point r = 0

$$E(r)= E(0) + (r\ddot{y})E(0) + ...$$

That part of V that creates a non-zero contribution to the matrix elements is equal to

$$V\ddot{y}\ddot{y}qr(r\ddot{y})E(0) = \ddot{y}q \sum_{ik} xixk \frac{\ddot{y}}{\ddot{y}xi} Ek , \qquad (4.96)$$

where xi denotes Cartesian coordinates. Each component of this quantity is a true scalar. The operator itself is such a scalar.
V, therefore its matrix elements in the states of the Zeeman multiplet are generally nonzero. Let us consider the effects associated with the presence of the component $(Ez)_z$ tensor $\ddot{y}Ek/\ddot{y}xi$. As will become clear
further, it is this component that leads to the emergence of dissociation-type effects in parallel MPs, that is, effects associated with
modulation of the phases of angular modes. We will not consider other components: they lead to resonant transitions in the multiplet only
at one, Larmor, frequency and, therefore, are of a less general nature.

Let us recall that Cartesian coordinates in the spherical coordinate system dinat equal

$$x = r \sin \ddot{y} \cos\ddot{y}, \; y = r \sin \ddot{y} \sin\ddot{y}, \; z = r \cos \ddot{y}.$$

In the first case, the component V, proportional to z2, does not act on
variable ÿ. Its matrix in the states of the Zeeman multiplet
diagonal, since only transitions with conservation of the magnetic quantum number are allowed. Let the z-component of the gradient of a scalar

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field Ez, which we will denote here for convenience as E , oscillates in time. Then

$$V = V \cos \ddot{y}t, \quad V = \ddot{y}qE\, z2 = \ddot{y}qE\, r2 \cos 2\, \ddot{y}.$$

You can immediately write down the equations for the coefficients of the desired wave functions of the ion in a constant magnetic field and a coaxial alternating gradient electric field. In the notation (4.59), using the expression HZ = ÿmÿ0 for the Zeeman Hamiltonian , we find

$$ic\ddot{y}m = cm\,(Vmm + HZ\, mm),$$

where does the solution follow?

$$cm = am \exp i\ddot{y}0mt\, \ddot{y}\, i\ddot{y}m \qquad \frac{1}{\ddot{y}} \sin \ddot{y}t\, ,\ddot{y}m = Vmm/\,.$$

Here am = cm(0), and the indices k and l are omitted for brevity. Therefore, the wave function has the form, see (4.57)

$$\ddot{y}klm = \sum_{kmm} aklmRklYlm \exp im\ddot{y}\, \ddot{y} \qquad \frac{i}{-}\ddot{y}klt + i\ddot{y}0mt\, \ddot{y}\, i\ddot{y}m \qquad \frac{1}{\ddot{y}} \sin \ddot{y}t\,.$$

The probability density of an ion near the gate is, see (4.6),

$$p(\ddot{y}0,t) = \sum_{mm} amm \exp im\, \ddot{y}0 + \ddot{y}0t + \frac{\ddot{y}1}{\ddot{y}} \sin(\ddot{y}t)\,,$$

$$\ddot{y}1 = \frac{\ddot{y}m\, \ddot{y}\, \ddot{y}m}{m}\,, \quad (4.97)$$

where m = m ÿ m. This expression repeats equality (4.8) for the density in parallel magnetic fields with the following clarification. In (4.97), the frequency ÿ1 has a different value associated with the amplitude of the change in the EP gradient. Therefore, the dissociation probability formula in this case is identical to (4.19). It is only necessary to substitute the new value of ÿ1 into (4.10). From relations (4.10) it is evident that only the argument of the Bessel functions z = mÿ1/ÿ=(ÿm ÿ ÿm)/ÿ, which determines the amplitude spectrum, undergoes changes in the dissociation probability formula. It follows that the dissociation frequency spectrum is still determined by the ion's cyclotron frequency and its harmonics

and their subharmonics. Relative weights of spectral maxima are associated with the coefficients amm , initial conditions of the ion in the capsule-le.

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We will also present formulas concerning the case when, in addition to the variable component, the EP gradient also has a constant component. Then

$$V = V (1 + ÿ \cos ÿt) ,V = ÿqE\ z2 = ÿqE\ r2 \cos2 ÿ,$$

where ÿ is the relative amplitude of changes in E · Solution of the equation on coefficients

$$cm = am \exp iÿ0mt ÿ iÿmt ÿ iÿm \qquad \frac{ÿ}{ÿ} \sin ÿt ,ÿm = Vmm/$$

gives the wave function

$$ÿklm = \sum_{kmm} aklmRklYlmÿ$$

$$ÿ \exp imÿ ÿ \qquad \frac{i}{—} ÿklt + iÿ0mt ÿ iÿmt ÿ iÿm \qquad \frac{ÿ}{ÿ} \sin ÿt .$$

Ion probability density

$$p(ÿ0,t)= \sum_{mm} amm \exp im\ ÿ0 + ÿ2t + \frac{ÿ1}{ÿ} \sin(ÿt) ,$$

$$ÿ2 = ÿ0 + \frac{ÿm\ ÿ\ ÿm}{m} ,ÿ1 = ÿ \frac{ÿm\ ÿ\ ÿm}{m} , (4.98)$$

again repeats equality (4.8) for the density in parallel MPs with
with the following clarification. In (4.98), the frequency ÿ1 has a different value. Also, instead of the frequency ÿ0, there is ÿ2. Therefore, the formula for the dissociation probability in this case is also similar to (4.19). It is only necessary to substitute the values of ÿ1 and ÿ2 into (4.10). From here it is easy to find, we omit the calculations, that relatively small constant gradients, that is, for ÿ> 1, lead to a shift in the positions of the frequency spectrum peaks. Due to the unpredictability of these constant gradients, averaging must be performed over them, which leads to a broadening of the calculated spectral maxima. For convenience's sake, we now return to the case of purely variable EP gradients.

Let's examine the amplitude spectrum of dissociation in a gradient electric field. We'll find the values of ÿm in the argument z:

$$ÿm = \frac{1}{—} Vmm = \frac{ÿqE}{z} Rkl(r)|r2|RklrYlm(ÿ, ÿ)| \cos2 ÿ |Ylmÿ,ÿ . \quad (4.99)$$

The integral ÿ = Rkl|r2|Rklr depends on the specific type of central potential. Since it is unknown, only its estimate can be given.

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The radial functions of a particle in a “box” of radius R are normalized by the condition
viem

$$\int_0^R |R(r)|\, 2r^2\, dr = 1 .$$

Extreme values of ÿ occur when the wave function is concentrated primarily near the center, or, conversely, near a surface of radius R. Their estimates are 0 and R2, respectively. We will use below the value ÿ = R2/2.

Calculation of the integral ylm = Ylm| cos2 ÿ |Ylmÿ,ÿ is reduced to repeated application of the recurrence relation [512], valid for |m| <l

$$\cos ÿ Ylm = Yl+1,m \sqrt{\frac{(l ÿ m + 1)(l + m + 1)}{(2l + 3)(2l + 1)}} + Ylÿ1,m \sqrt{\frac{(l + m)(l ÿ m)}{ÿ 1)(2l + 1)}}.$$

Taking into account the orthonormality of spherical functions, we find:

$$ylm = 2 \sqrt{\frac{(l ÿ m)(l + m)(l ÿ m + 1)(l + m + 1)}{+ 1)(2l + 3)(2l + 1)}} .$$

Let us consider the case l = m separately. The spherical functions defined by formulas (4.73), (4.74) contain associated Legendre functions P ml , which for m = l are equal to

$$Pl l(x) = (2l ÿ 1)! (1 ÿ x2)\, l/2 , x = \cos ÿ.$$

Here, the modified factorial ! means omitting even terms in the corresponding product. Next, we find Yll and

$$yll = \frac{(2l + 1)[(2l ÿ 1)!\,]^2}{2(2l)!} \int_{-1}^{1} (1 ÿ x2)\, l\, x2\, dx .$$

The value of the last integral is given in [379]:

$$Int = ÿ(l + 1)ÿ (3/2) /ÿ(l +5/2) .$$

Using the properties of the gamma function

$$, ÿ(3/2) = ÿÿ/2 , ÿ(n +1/2) = (2n ÿ 1)!\, ÿÿ/2\, ÿ(l + 1) = l!$$

and the ratio

$$(2n ÿ 1)! = \frac{(2n ÿ 1)!}{2nÿ1(n ÿ 1)!} ,$$

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we get yll = 1/(2l + 3). With Kronecker symbols, the general expression for numbers ylm takes the following form:

$$ylm = Ylm|\cos 2\ddot{y}\,|Ylm\ddot{y},\ddot{y} = \frac{1}{2l+3}\ddot{y}lm + 2\frac{(l\ddot{y}m)(l+m)(l\ddot{y}m+1)(l+m+1)}{(2l\ddot{y}1)(2l+1)(2l+3)(2l+1)}(1\ddot{y}\ddot{y}lm).$$

It can be shown that the asymptotic behavior of this function as l ÿ ÿ is

$$ylm = 1\ddot{y}(m/l)^2/2. \qquad (4.100)$$

For small l, starting from unity, the error of this formula when calculating differences is 10–15%, which is quite sufficient for estimates. The difference in the values of ylm for different values of m, which will now be needed, is obviously equal to

$$ylm\ddot{y}ylm = 2l2\frac{m2\ddot{y}m2}{}.$$

Returning to expression (4.99), we write it as follows:

$$\ddot{y}m = \frac{\ddot{y}qE\ddot{y}}{}ylm,$$

accordingly, the argument of the Bessel functions takes the form

$$z = (\ddot{y}m\ddot{y}\ddot{y}m)/\ddot{y} = 2l2\frac{m2\ddot{y}m2}{}\frac{qE\ddot{y}}{\ddot{y}}. \qquad (4.101)$$

Unlike the case of parallel MPs, the argument contains the difference squares of the magnetic quantum numbers, not m. This means that angular modes that differ only in the sign of m do not interfere. Indeed, an electric field, as is well known, does not lift the degeneracy by the sign of m, therefore, the behavior of the phases of these modes in the electrical field le is identical.

Due to the unpredictability of the value of ÿkl and statistical weights states with different l, it is possible to estimate only the lower limit of the effective values of E · Fine structure of the amplitude spectrum of the motif Jn(z) will inevitably blur when averaging over several parameters, having statistical meaning, including the magnitude and direction of the EP gradient. Obviously, to estimate the threshold values of E, we should set l = 1 and, accordingly, m2 ÿ m2 = 1. For ÿkl , we use,

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as found above, the estimate ÿ R2/2. Having represented the frequency of the external field ÿ in relative form ÿ= f qHDC/M c, we write the argument in the form

$$z = \frac{EM\ cR2}{4f\ HDC} .$$

In Section 4.1 it was shown that the first maximum in the dissociation response to the magnetic field occurred at z = 1.8 at a frequency f = 1/2. Substituting these values, we find, by order of magnitude,

$$E\ ÿ \quad \frac{HDC}{M\ cR2} = \frac{ÿc}{qR2} \sim 0.2 \text{ CGS units (cmÿ3/2g 1/2sÿ1) .} \qquad (4.102)$$

It would be interesting to compare this level of field gradients required for the appearance of interference effects with those of macro- and microscopic gradients that exist in the real cellular environment.

Below, for convenience, we will talk about the EP gradient in a broader sense, understanding by this, naturally, a certain averaging over the components of the tensor ÿEi/ ÿxk, which could characterize the value heterogeneity of the EP.

The magnetic field on the microscale is almost identical external magnetic field. On the contrary, the electric field in the biological environment, induced by the external field, has non-uniformity due to differences in the polarizability of various biological subsystems, such as intercellular and intracellular plasma, organelles, membranes, etc. Penetrating into the tissue, the EP decreases due to the polarization of the surface layers of the tissue and, in addition, acquires a non-uniform spatial structure. Inhomogeneity of the electric field on on a microscale is also due to the presence of charged particles in the environment particles and dipoles.

4.6.2 Electrical gradients in biological tissue no

Gradients due to non-uniform polarization

The most probable site of the primary processes of EMF reception is considered to be the surface of cell membranes [239]. Appendix 6.4 shows that, within the framework of the continuous medium approximation, the EP gradients on the surface of biological cells are close in order of magnitude to E/Rc, where Rc is the cell size. Substituting this value into (4.102) and using

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parameters of the Ca2+ ion in the Earth's magnetic field and the cell size of ÿ 10ÿ3 cm, we obtain assessment of the threshold value of the EP causing the effect

$$\text{Eth} \ddot{y} \quad \frac{\ddot{y}c}{qR}\frac{Rc}{R} \ddot{y} 25 \text{ V/m} . \qquad (4.103)$$

Thus, gradients of magnitude (4.102) arise on the surface cells in the presence of an electric field of order (4.103) inside the environment. These gradients have a macroscopic, cell-size-scale heterogeneity.

There are other sources of gradient fields in the cellular environment. Firstly, free ions present in the physiological environment due to the electrolytic dissociation of various inorganic salts. Typically, these are chloride NaCl, bicarbonate NaHCO3 , and phosphate Sodium NaH2PO4 , potassium chloride KCl and calcium chloride CaCl2 , and magnesium sulfate MgSO4. Chloride and sodium ions are present in the highest concentration, ~0.1 M (mol/liter), and they make the main contribution to the electrical conductivity of the tissue. Secondly, in the biological environment there are molecular and subcellular structures that possess electrical dipole moment, which are also sources of electrical gradients. When an external alternating EF is applied, a component coherent with the external field appears in the dynamics of ions and dipoles. As a consequence, variable microscopic field gradients also arise. Let us conduct the necessary assessments.

Free ions in the electrolyte

The movement of ions in an electrolyte can be easily imagined by comparing the following characteristic dimensions:

— the average distance between ions,
— the amplitude of the ion drift in an alternating electric field,
— diffusion displacement of the ion during the period of EP oscillation,
— the characteristic size of the possible region of ion residence.

Average distance between ions at a given concentration c [M] equals

$$\bar{r} = 10 (N_A c)^{\ddot{y}1/3} \text{ [cm]} .$$

For the above concentration of 0.1 M this would be 2.5 nm.

In electrochemistry, the mobility u of ions is defined as the proportionality coefficient between the drift velocity v and the macroscopic EF strength in solution E, that is, v = uE. In the field E = E0 cos ÿt drift displacement is obviously equal to (uE0/ÿ) sin ÿt.

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The mobility of ions in biological tissues is close in order of magnitude to 10ÿ7 m2/V s. In the Gaussian system, this is equal to u ÿ 0.3 cm3/2 gÿ1/2. In the EP magnitude ÿ 1 V/m and frequency ÿ ÿ 100 Hz, the ion displacement amplitude will make up

$$r = uE0/ÿ \ ÿ \ 1 \text{ nm} .$$

At the same time, the diffusion displacement over time t = 2ÿ/ÿ, determined by the formula r2ÿ 6Dt, is several orders of magnitude larger. If we use Einstein's relation for the diffusion coefficient
D ÿ ÿT u/q, see, for example, [124], then it is easy to find that

$$rd \ ÿ \ 2ÿ \sqrt{\frac{ÿT \ u}{qÿ}} \ ÿ \ 30 \ \mu m.$$

This means that the movement of conductivity ions is predominantly random. From the point of view of the putative receptor
In the case of EMFs of molecular or even cellular dimensions of ~1 µm, regular drift displacements are unnoticeable against the background of much more intense random walks. It follows, in particular, that the redistribution of ion density under the influence of such a variable
the external field is too small to have a noticeable effect on
the functioning of biophysical systems. Due to their obvious insignificance, the regular component of the EP and its gradients from moving free ions does not require evaluation.

Dynamics of macromolecular dipoles

The random component in particle dynamics in solution is significantly reduced for relatively massive particles. It is known that some molecules in biological tissue, including large subcellular structures and even some types of cells, are electrically polarized or

have a significant dipole moment, from units to thousands of D
[167, 613].

The rotational dynamics of a massive dipole d in a viscous medium in an electric field E is described by the equation

$$Iÿ¨ \ ÿ \ ÿÿÿ = Ed \sin(ÿ \ ÿ \ ÿ0) , \qquad (4.104)$$

in which ÿ is the angle between E and the dipole axis, I is the moment of inertia, ÿ — the attenuation coefficient. The right-hand side of the equation is the torque dU/dÿ acting on the dipole from the electric
fields, since the dipole energy is equal to U = ÿdE = ÿEd cosÿ.

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The external EP causes rotational oscillations of the dipole, which lead to the appearance of a variable component in the electric field gradient around the dipole. This component can cause an interference effect of dissociation of the ion experiencing the action of the gradient. For interference to occur, it is necessary that the gradient oscillations represent a more or less regular process.

with an autocorrelation time exceeding the characteristic time ÿ ÿ
0.1 s of dissociation of the ion-protein complex. However, due to rotational diffusion, not all dipoles will create sufficiently coherent gradient oscillations around themselves. Obviously, the characteristic rotational diffusion time must be greater than ÿ, then
at time intervals <ÿ the dipole dynamics are regular enough that cause interference. This imposes a limitation on the size of the diploma-
la.

For estimating orders of magnitude, the idealization of a spherical shape is convenient, radius R, dipole. Then, in a medium with a viscosity coefficient ÿ, the characteristic time of diffusion rotation by 2ÿ is approximately equal to, see [124], ÿR3/ÿT . From this we find that in order to satisfy the condition of sufficiently coherent dynamics, the size of the dipole must exceed

$$R ÿ \quad ^{3} \overline{ÿÿT /ÿ ÿ} \; 0.6 ÿm \quad , \qquad (4.105)$$

where physiological temperature and viscosity are used in the assessment water ÿ ÿ 10ÿ3 Pa s or 10ÿ2 g/cm s in the Gaussian system. We will assume that similar dipoles are present in the biological environment. In in particular, these may be the biological cells themselves, which have dipole moment, intrinsic or induced.

Having written equation (4.104) for the dimensionless independent variable ÿt ÿ t, it is easy to establish that dipoles of the specified size are overdamped, since the coefficient at ÿÿ is much greater than the coefficient at ÿ¨. Their ratio is equal to

$$ÿ/Iÿ ÿ 106 .$$

This estimate uses the formulas ÿ ÿ 4ÿÿR3 [124], I =2MR2/5,
M = ÿ4ÿR3/3, ÿ is the average density of the dipole substance.

Taking this into account, in an alternating field with amplitude E0 the equation has view

$$ÿÿ = \frac{ÿE0d}{ÿÿ} \sin t \sin(ÿ ÿ ÿ0) .$$

The coefficient E0d/ÿÿ, in the ranges of variation of these quantities that interest us, is much less than unity. Therefore, the derivative ÿÿ is also small,

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so that the value of sin(ÿÿÿ0) is practically constant and is determined by the initial orientation of the dipole ÿ0. From this follows an estimate of the oscillation amplitude ÿÿ of the variable ÿ

$$ÿÿ \; ÿ \; E0d/ÿÿ \; . \qquad (4.106)$$

Knowing the amplitude of the field-induced rotations, one can determine the amplitude of changes in the gradient of the electric field of the dipole. The dipole field is determined by the expression

$$E(r)= r3 \; \frac{3(nd)n \; ÿ \; d}{} \; , \qquad (4.107)$$

where n is a unit vector in the direction of the vector r from the dipole to the point, where the field is defined. An approximate characteristic of the inhomogeneity of the vector field at point r could be the divergence of the field ÿE, summing the diagonal elements of the tensor ÿEi/ÿxk. Using differential relations

$$ÿ(rn)= nrnÿ2r \; , \; ÿ(rd)= d \; , \; ÿ(fr)=3f +(ÿf)r \; ,$$

where d is a vector and f is an arbitrary scalar function, we calculate the sum of the moduli of the elements

$$|ÿ|E = 12nd/r4 = 12d \cos ÿ /r4 \; .$$

Here the angle ÿ is the angle between the dipole axis and the direction to the point where the inhomogeneity of the field is determined. The order of the derivative |ÿ|E with respect to the angle is equal to 12d/r4, therefore, the required amplitude g of changes in the field inhomogeneity during oscillations of the dipole axis will be

$$g \; ÿ \quad \frac{1}{ÿ} \; (12d/r4)ÿÿ \; ÿ \; \frac{12E0d2}{ÿr4ÿÿ} \; ,$$

where the relation (4.106) is used and the shielding effect is taken into account polarizable medium with permittivity ÿ. Near the dipole r ÿ R, in addition, it can be assumed that the dipole moment is proportional to the size of the dipole, d ÿ 2Rq, where q is the equivalent charge dipole poles. Then, substituting also ÿ ÿ 4ÿÿR3, we obtain the estimate amplitudes of EP gradients

$$g \; ÿ \quad \frac{4E0q2}{ÿÿÿR5} \; \sim 0.02 \text{ CGS units } (cmÿ3/2g \; 1/2sÿ1) \; . \qquad (4.108)$$

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In this estimate, we used the specified dipole size (4.105), an electric field of 25 V/m or 25 · 0.333 · 10ÿ4 CGS units, and a permittivity of water of ÿ ÿ 80. This estimate is an order of magnitude smaller than the value required to cause interference, (4.102). Considering the quadratic dependence on the equivalent charges of the dipole poles, which can significantly exceed the elementary charge, this agreement could be considered satisfactory. At the same time,

time, the strong dependence on the size of the dipole requires that the point observation, or reception, of gradients was not too far from the dipole. If we are talking about a cell suspension, then its density should
be large enough that the distance between the dipole cells
was of the order of the cell size. Then targets located on the surface of one of the cells could perceive the gradients created by the neighboring cell. It is easy to calculate that the density of such a suspension
should not be lower than 1010 cmÿ3. If the dipoles are subcellular macromolecules, then there are no restrictions on the suspension density.

■ Thus, low-frequency, f ÿ 10 Hz, EP of magnitude 10–
100 V/m give approximately the same contribution to the variable component of the EP inhomogeneity in the medium, both due to the inhomogeneous dielectric polarization within the framework of the continuous medium approximation, and due to the modulation of the rotational dynamics of macrodipoles. In both cases, the scale of the inhomogeneity is macroscopic, on the order of 1 µm, and its
the magnitude is apparently insufficient for interference effects.

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4.6.3 Gradients due to electronic polarization of ligands

Finally, there are EP gradients created by induced dipole moments of nearby binding ligands. They arise due to the displacement of the electron shells of the ligands in the external EP. Let us estimate the order of magnitude of the field inhomogeneity by considering the binding cavity of ligands as an induced dipole.

of size 2R, where R is the radial size of the cavity. The magnitude of the dipole moment is d ÿ ÿE, where ÿ is the electronic polarizability of the ligand atoms, equal in order of magnitude to 10ÿ24 cm3. On the other hand, the effective electric charge Q of the dipole poles is associated with its
dipole moment with the ratio Q ÿ d/2R. It is easy to determine,
using Coulomb's law, that the gradient of the EP in the center between the poles

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dipole axis is equal

$$g \ddot{y} 4Q/R3 = 2\ddot{y}E/R4 .$$

By equating this value with (4.102), we find the amplitude of the field in the medium necessary for interference effects caused by the electronic polarizability of the ligands [304]:

$$Eth \ddot{y} \frac{\ddot{y}cR2}{2q\ddot{y}} . \qquad (4.109)$$

In order of magnitude, this is 4 10ÿ8 CGS units or 1 mV/m. The estimate was obtained within the framework of fairly strong idealizations. In particular, the magnitudes of the gradients vary greatly across the cavity volume. Even taking this into account, the estimate is sufficient to explain some experimental data, where the amplitude windows of the effect of the biological action of weak variable EP appear at somewhat higher field strengths.
Let us recall that estimate (4.109) refers to the internal electric field averaged over a physically small volume of the biological environment. The assessment determines the lower limit of effective EP. This means that expected dependence on the magnitude of the internal electric field has the following form

$$J2 1(1.8E/E\ddot{y}) , \qquad (4.110)$$

where Eÿ >Eth. As already mentioned, the a priori estimate of the value of Eÿ is difficult due to the many biological parameters on which it depends.

One of the predictions of the interference mechanism in EP is in the fact that *resonant interference in perpendicular magnetic fields can be destroyed by turning on an electric field* parallel to a constant magnetic field. Indeed, some biological
The effects of magnetic fields are associated with the Zeeman splitting of energy particle levels in a geomagnetic or other constant magnetic field. This is evident from observations of the biological effectiveness of magnetic vacuum. Then static EFs of the order of 10–100 V/m should also influence on the indicated effects, since they lead to the same magnitude splitting of levels. This means that it is advisable to conduct magnetobiological experiments in a Faraday chamber or under control constant EP. Note that the measurement of local constant EP requires the use of special devices, such as a rotating dipole.

Relation (4.109) shows that the lower limit of the EP Eth, and hence the characteristic field Eÿ in (4.110), are in the straight line

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proportions to the cyclotron frequency ÿc or to the magnitude of the constant magnetic field HDC. Another related prediction is that *the position of the maximum in the dependence of the MBE on the amplitude of the alternating EF shifts proportionally to the level of the constant MF.* This prediction is valid over a relatively wide frequency spectrum. Otherwise, the effect will decrease at a fixed frequency ÿ.

with a change in the static MP due to the deviation of the characteristic frequencies ÿc from ÿ.

■ As shown in Section 4.5, the MBE by the ion interference mechanism can develop in a constant magnetic field in the presence of rotating ion-protein complexes. This effect obviously also depends on the presence of a constant EP, from its magnitude and orientation. It is known, that the Earth's EP, associated with its electrical potential, is subject to strong local changes depending on the state of the atmosphere.
For example, the vector of a quasi-static EP of the scale kV/m can even acquire the opposite direction when a cloud appears above this place [278]. Thus, the change in weather is accompanied long-term change in the relative direction of the EP and its magnitude. This is important for rotating ion-protein complexes and, generally speaking, can lead to final biological reactions.
According to data [69], among people susceptible to cardiovascular pathologies, there are twice as many who react to variations in MP than those who react to variations in local atmospheric pressure. Not It is possible that pressure variations also have an indirect effect through the local EP variations that correlate with them.

4.7 Interference in the presence of magnetic noise

The interference mechanism is nonlinear in the sense that
The response to the total signal A+B is not equal to the sum of the responses to each of the signals separately. In addition, the ion interference mechanism has another feature that allows it to be distinguished from other nonlinear mechanisms. The probability of dissociation of the ion-protein complex P in the ion interference mechanism
is, mathematically, a nonlinear functional of the MP signal.
This means that if it is possible to transform such a functional to an explicit function of the parameters of possible signals, then the form of this function depends, generally speaking, on the type of signal. Let, for example, some

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the deterministic signal of the MP leads to constructive interference described by some functional dependence. Then
The imposition of an additional MP changes the appearance of this dependence.

Noise MP has an interesting feature in this regard.
The modified dependence on the MP parameters in this case decomposes into a product of two functions. One of them is a dependence on the MP parameters in the absence of noise. The second, on the contrary, depends only on parameters of magnetic noise and represents a modulating coefficient of less than unity. The effect of magnetic noise is reduced
thus leading to the suppression of MBE.

For convenience, let us consider interference in parallel MPs.
Section 4.1 shows that the probability density of an ion at a certain angular position ÿ0 is determined by the sum of terms of the form

$$p = \exp im(ÿ0 + ÿ0t + bh\,dt) .$$

In the current section, this summation is not essential and we omit it without loss of generality of the conclusions. Let the variable MP h consist of deterministic signal h1 and noise:

$$h = h1(t) + ÿÿ(t) ,$$

where ÿ(t) is a centered, i.e. zero-mean, random process with unit variance, and ÿ is the standard deviation,
that is, the square root of the variance ÿ2 of the noise signal ÿÿ(t),ÿ
the dimension of the MP. Then we write the probability density as

$$p = p \exp i \qquad ÿ(t)\,dt) , \qquad = mbÿ.$$

Here p is that part of the density p that depends on the parameters of the deterministic signal.

We will assume that the random process ÿ is ergodic. Then its statistical characteristics, in particular, the average values of the functions of ÿ,
can be obtained from just one of its realizations, by averaging
in time. Let's assume that we have a segment of such implementation.
Let the length of the segment ÿ exceed all time scales inherent in the simulated real physical system. Then the realization of ÿ(t)
random process ÿ can be constructed by repeating such segments

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kov, and, as a periodic function, can be represented by a Fourier series

$$ÿ(t)= \sum_k dk \exp(iÿkt)= \sum_k ck \cos(ÿkt + ÿk) ,ck = |dk| ,ÿk = k. \frac{2ÿ}{ÿ} \tag{4.111}$$

The longer the interval ÿ, the closer the random real values are.
spectral amplitudes ck and phases ÿk to deterministic values determined by the spectral density G(ÿ) of the process ÿ.

Let us recall that the spectral density of a centered stationary, that is, with constant statistical properties, random process ÿ is the quantity

$$G(ÿ)= 2ÿ \frac{1}{ÿ} \int_{ÿ}^{ÿ} \overline{ÿ(t)ÿ(t + ÿ)}eÿiÿÿ \, dÿ \quad ,$$

where the overbar denotes averaging over time. A specific realization ÿ(t) of a random process ÿ can be represented by a Fourier integral

$$ÿ(t)= \int_{ÿ}^{ÿ} ÿÿeÿiÿtdÿ . \tag{4.112}$$

The spectral amplitudes ÿÿ are random functions on the ensemble of realizations and satisfy the relation

$$\overline{ÿÿ \, ÿÿÿ} = G(ÿ)ÿ(ÿ) . \tag{4.113}$$

A detailed introduction to the applied theory of random processes is contained, for example, in the monograph [11]. Assuming that the realization ÿ(t) is periodic with a large period ÿ, we obtain a discrete spectrum with a dense frequency series ÿk. The spectral decomposition in this case has the form of a series rather than a Fourier integral, which is convenient for further analysis.

Substituting the cosine expansion (4.111) into p, we write

$$p = p \exp i \sum_k \frac{ck}{ÿk} \sin(ÿkt + ÿk) = p \prod_k \exp i \frac{ck}{ÿk} \sin(ÿkt + ÿk) .$$

We use formula (4.11), then

$$p = p \prod_{kn} Jn(ak) \exp [in(ÿkt + ÿk] ,ak = ck/ÿk.$$

This expression is reduced to the sum of the products of a large number of Bessel functions, among which there are also products of Bessel functions.

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functions with equal orders. Since |Jnlÿ 1, the only contribution that does not vanish in the limit ÿ 0 is the product of Bessel functions
functions of zero order.8 Therefore,

$$p \ddot{y} p \quad J0(ak) .$$
$$k$$

In addition to p, this expression includes a coefficient that does not depend on
from time and is determined only by parameters that are relevant
to magnetic noise. Therefore, in the expression for the dissociation probability P = pT · pT, this coefficient appears as a modulating
multiplier y:

$$y = \quad J2\ 0(ak) . \qquad (4.114)$$
$$k$$

This coefficient is equal to unity at = 0, that is, in the absence of noise, and tends to zero
effects disappear. To determine the nature of with increasing noise intensity, the interference

From this dependence we find the first terms of the expansion of y in a series in powers small parameter ak. Note that in the argument of the Bessel functions
not only proportional to the amplitude of the noise signal, but also the values ak = ck/ÿk take small values, the smaller the more
the frequency range of the noise spectrum is dense. It is convenient for us to represent J0(x) in the region of small values of x in the form of an exponential with a series in its exponent

$$J0(x) = \exp(ax2 + bx3 + ...) , \qquad (4.115)$$

it starts with a quadratic term since J 0(0) = 0. From the expansions

$$\exp(x)= \quad \frac{xn}{n!} , \quad J0(x)= \quad (\ddot{y}1)n \frac{(x/2)2n}{(n!)2}$$
$$n=0 \qquad\qquad n=0$$

we can determine the coefficients in (4.115), a = ÿ1/4, b = 0. We will not look for the remaining terms of the expansion, due to their insignificance. Then

$$y = \quad \exp(\ddot{y}a2\ k2/4 \quad ^2 = \exp \quad ^{-2} \frac{c2_k}{2} \quad \frac{}{\ddot{y}2_k} \quad .$$
$$k$$

Let us replace the dense discrete frequency spectrum ÿk with a smooth function G(ÿ). In this case, the spectral amplitudes of the discrete series ck (4.111)

8A detailed examination taking into account terms of order o(2) confirms this conclusion.

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transform into functions ÿÿ, (4.112), for which the relation is valid
(4.113) In fact, one should write c2 k ÿ G(ÿ)dÿ. Then the last
equality, substituting the value can also be written in the following
view

$$y = \exp\left[\ddot{y}\ddot{y}2\frac{b22m}{2} \int \frac{G(\ddot{y})}{d\ddot{y}} \cdot \ddot{y}2 \right] \qquad (4.116)$$

This means that with increasing intensity of magnetic noise, that is,
dispersion ÿ2, interference effects are non-trivially weakened.
Note that the integral in (4.116) converges, since the spectrum of G(ÿ) is
bounded below by at least the frequency ÿÿ1. The spectrum of G(ÿ) enters y through
integral, which indicates a relatively weak dependence of y on the details of the spectrum
shape.

Let, for example, the magnetic noise spectrum be uniform in the interval ÿ1,ÿ2. Then
G(ÿ)=(ÿ2 ÿ ÿ1)ÿ1, and the integral in (4.116), as is easy to verify, is equal to 1/ÿ1ÿ2. The
value of this integral differs by
20–30%, if we use a good, that is, one that ensures convergence, Gaussian spectrum
centered at the point (ÿ1 + ÿ2)/2. The dependence of the modulating factor on the noise
intensity takes
for a uniform spectrum view

$$y = \exp\left[\ddot{y}\ddot{y}2\ 2\ddot{y}1\ddot{y}2\frac{b22m}{} \right] .$$

The noise intensity at which the interference effect begins to weaken is determined by the
equation y = exp(ÿ1/2). From this
It is easy to find the characteristic value of the root-mean-square amplitude ÿ =
ÿÿ1ÿ2/bm. The greatest contribution to the dissociation probability comes from
the interference of modes with a difference in magnetic quantum numbers m = 1, 2.
Since the cyclotron frequency is proportional to the constant magnetic field,
ÿc =2bHDC, then for the threshold amplitude it is convenient to write the following
ratio

$$\frac{\ddot{y}}{HDC}\ \ddot{y}\ \frac{\ddot{y}\ddot{y}1\ddot{y}2}{\ddot{y}c}, \qquad (4.117)$$

that is, *the relative amplitude of magnetic noise suppressing ion interference is proportional
to the relative magnitude of the geometric mean of the frequencies of the edges of the noise*

spectrum. It is important that the effect of the noise factor manifests itself mathematically
as a modulating factor, independent of the specific interference mechanism.

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4.7.1 Correlation with experimental data

It is probably this phenomenon, the suppression of the MBE by magnetic noise, was repeatedly observed in T. Litovitz's group in experiments with simultaneously acting deterministic EMF signals of various types and magnetic noise. Mullins, Krause and Litovitz [582]
showed that the increase in ornithine decarboxylase activity under the influence of 60 Hz MF on rodent L929 cells is suppressed by low-frequency magnetic noise. Litovitz, Krause et al. [693], Litovitz, Montrose et al. [685] observed a decrease in the level of deviations from normal development of chicken embryos caused by low-frequency sinusoidal MF under the influence of low-frequency magnetic noise.

Lin and Goodman [531] confirmed these results in MBE with persistently elevated levels of *c-myc* proto-oncogene transcription in HL-60 cells under 60 Hz sinusoidal MF. Superposition of magnetic noise with a frequency band of 30–100 Hz and a root-mean-square amplitude of 6.7 ÿT suppressed MBE. Litovitz, Penafil et al. [306] measured ornithine decarboxylase activity in L929 cells under conditions of amplitude-modulated microwave radiation, radiation

a typical cell phone with modulation, as well as under conditions of a homogeneous low-frequency magnetic field. In all cases, the enzyme activity increased as a result of the radiation. Additional simultaneous
exposure to narrowband magnetic noise in the 30–100 Hz band with
with an effective amplitude of 2–5 ÿT resulted in suppression of the effect. Another study on this topic was conducted by Raskmark and Kwee [625].
The MBE consisted of increasing the growth rate of human epithelial cells under the influence of a sinusoidal magnetic field with a frequency of 50 Hz. Simultaneous The imposition of noise with a bandwidth of 40–60 Hz in the range up to an RMS amplitude of 50 ÿT also reduced the level of MBE.

It makes sense to introduce dimensionless quantities

$$ÿ = ÿbH/\ ÿ2ÿ1\overline{ÿ2}\ ,b = b/bH\ ,$$

where bH = e/2mpc is the charge-mass ratio of the hydrogen ion. In these In notations, the formula for the suppression coefficient has a particularly simple view

$$y = \exp ÿÿ2b2\ . \qquad (4.118)$$

Note that all parameters of magnetic noise are contained in its relative amplitude ÿ . This is quite convenient, since it allows us to compare many different experimental data with a single theoretical curve, within the framework of the hypothesis of the involvement of some

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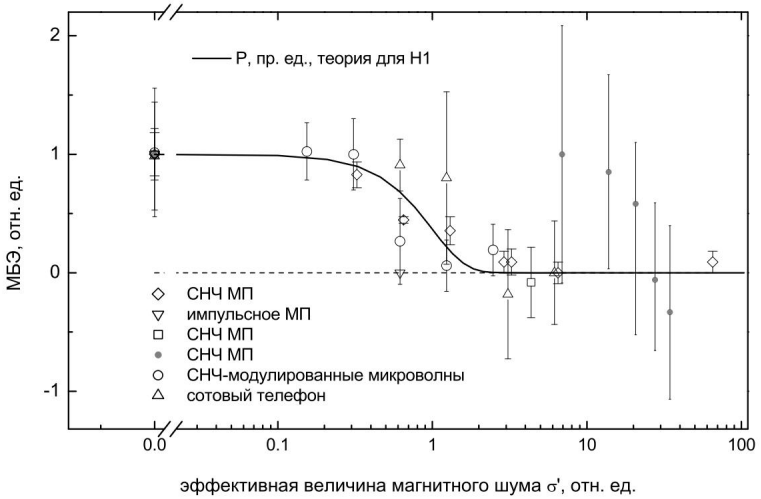


Fig. 4.26: Dependence of various MBE on the magnetic noise level and typical theoretical decay curve of dissociation probability in pre-the position of participation of hydrogen ions as primary targets of the magnetic field, ÿ [693], ÿ [685], [531], • [625], O, [306].

a certain type of ions. Our choice corresponds to hydrogen ions, b = bH = 47.8 sÿ1 ÿTÿ1.

The data from the above experiments were normalized as follows. The maximum MBE for each experiment was taken as one, and the control level as zero.

Fig. 4.26 shows the experimental data [693, 685, 531, 625, 641] and the theoretical curve calculated using formula (4.118) for hydrogen ions. It is evident that the theoretical conclusions are in satisfactory agreement with experiment. In this case, the theoretical The curve has the character of an estimate. Therefore, the identification of ions according to the correspondence between theory and experimental data, although possible under specially developed magnetic conditions, is hardly possible in relation to the indicated experiments. Rule (4.116) gives a specific dependence on the parameters of the magnetic noise spectrum and provides another way of experimentally testing the general provisions of the theory.

The data of Raskmark and Quee [625] are more consistent with the hypothesis of involvement in magnetoreception of lithium ions, bLi = 6.87 (s · ÿT)ÿ1.

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Lithium ions, as well as hydrogen, calcium, magnesium and zinc ions, were discussed as possible MP targets by Thomas, Schroth and Liebow in [696], Smith in [665]. Polyextreme spectra of MBE on neurons measured by Blackman, Blanchard et al. [421] and Blackman, Benan and House [317] were explained by the author in [300] on the assumption that lithium ions form complexes with rotating proteins.

It remains to determine the maximum values of ÿ for which formula (4.118) is still valid. Obviously, returning to (4.115), we must write x = ck/ÿk 1. For a uniform spectrum within [ÿ1,ÿ2], $c_2^2 = c2 = 1/K$, where K is the maximum number of the discrete frequency series, for $k \; c_k^2 = 1$. Obviously, this number is equal to the ratio of the upper boundary of the spectrum to the low frequency ÿÿ1, determined by the length of the periodicity interval of the noise realization K = ÿ2ÿ. Consequently, c ÿ 1/ÿ2ÿ. On the other hand, to have a guaranteed estimate, we must take the minimum of the frequencies ÿk, that is, ÿ1. Then in ÿk/ck ÿ ÿ1 ÿÿ2ÿ. relative units this constraint has the form

$$\frac{ÿmax}{HDC} \quad \frac{ÿ1}{ÿc} \quad \overline{ÿ2ÿ}.$$

If the repeating segments in the realization of the noise signal have length of not less than ÿ = 10 s, which is completely accessible in the experiment, then, Substituting the values ÿ1 and ÿ2 used above , we obtain on average ÿ HDC. In this range, the calculated curve closely approximates expression (4.114). The length of the periodicity interval ÿ, of course, can be increased. Then the interval of validity of formula (4.118) will also increase. In fact, this means that the measurement of small values

functions y in the region of large ÿ require more observation time. When measuring the suppression of the MBE by noise for more than 10 minutes, i.e. ÿ> 600 s, the limits on the permissible value of magnetic noise correspond to the level of constant magnetic field.

■ Generally speaking, the scatter of data in magnetobiological experiments is usually so great that the need to obtain any mathematically precise estimates simply does not arise. Comparison of the qualitative course of the curves provides much more reliable information here. information rather than a comparison of precisely measured and precisely calculated quantities.

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4.8 Nuclear spins in the mechanism of ion interference

The energy of the nuclear magnetic moment of an ion ÿ ÿH in the magnetic field H is somewhat larger than the scale of the energy of the orbital magnetic moment ÿ ÿc. Therefore, spin effects are important in the action of weak magnetic fields on the dynamics of bound ions. Spin-mediated interference of the states of a bound ion leads to a shift in the interference spectrum in
region of higher frequencies. Observation of this effect is possible,
if the lifetime of the nuclear spin states of the ion is sufficiently long, greater than the characteristic time scale of interference, determined by the frequency of the external field: ÿN > ÿÿ1. In this section, this idealization is adopted, the validity of which must be established

experimentally, from the good agreement between the calculated and experimental spectra. Since the ion in the binding cavity oscillates at a microwave frequency, the electric field gradients induced by thermal vibrations of the capsule walls and "visible" by the spin are averaged. Accordingly, the relaxation of the spin state is hindered. For example, the high mobility of protons in liquid water also allows

they “see” only the average gradient of the microscopic electric field and leads to an anomalously long lifetime of the spin states of protons ÿ 3 s. There are, therefore, grounds

consider the spin states of ions in long-lived binding cavities
evolving states.

As shown in Section 3.10.1, the dynamics of bound ions with
the spin of the nucleus depends on which approximation, strong or weak
MP, takes place. The transition region approximately corresponds
or somewhat larger than the geomagnetic field, so it is not known *a priori ,*
which approximation is closer to reality.

In a relatively strong magnetic field, spin dynamics develops independently of orbital dynamics. The dynamic equation has the form
Pauli

$$i\,\frac{\ddot{y}\ddot{y}}{\ddot{y}t} = \frac{(P\,\ddot{y} - \frac{q}{c}A)2}{2M}\,\ddot{y}\,\ddot{y}I\,H + U\,\ddot{y} \quad ,$$

which allows for separation of variables in the solution

$$\ddot{y} = \ddot{y}(r, \ddot{y}, \ddot{y})\ddot{y}(\ddot{y}) \ ,$$

where ÿ and $\ddot{y}= i\,ai\ddot{y}i$ are functions of the spatial and spin variables. Interference implies the presence of an interference term in the probability density of an ion near the gate. The probability density

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, the square of the modulus of the scalar field ÿ, in some angular position
there is a woman

$$p = ÿ\text{Ÿ}r,ÿ,ÿ = ÿ\text{Ÿ}r,ÿ \qquad aiÿi|akÿk = ÿ\text{Ÿ}r,ÿ \qquad aÿ_{ai} \ . \ (4.119)$$
$$ik \qquad\qquad i$$

Here, the indices near the angle brackets mean averaging over the corresponding variable, r, ÿ, or ÿ. Since the spin functions are orthogonal, that is, ÿiÿk = ÿik, the density is equal to the sum of the densities due to each of the spin components.

It was shown earlier (4.6) that the quantity ÿŸr,ÿ contains terms due to the interference of angular modes with different values of the magnetic quantum number m. At the same time, the density (4.119)
does not contain terms proportional to the product of the amplitudes of different spin modes aÿ i ak. In this sense, we can say that the spatial modes of the wave function corresponding to different values of the spin variable do not interfere. This means the absence of spin-

conditioned interference effects in the strong approximation
fields.

4.8.1 Spin-dependent interference in a weak magnetic field

In a relatively weak magnetic field, the spin-orbit interaction of the ion with
spin in the central potential is essential:

$$H = \frac{P^2}{2M} + U(r)\ ÿ\ (bL + ÿI\ )\ H + Hso \ . \qquad (4.120)$$

Magnetic interactions are weaker than spin-orbit interactions and magnetic ha-
Miltonian

$$HM = ÿMH = ÿ(bL + ÿI\ )H$$

can be considered a perturbation for the unperturbed Hamiltonian

$$H0 = \frac{P^2}{2M} + U(r) + Hso \ .$$

The solution of the Schrödinger equation with a given Hamiltonian is no longer reduced to the product of the orbital and spin functions. It is formed by a superposition of the eigenfunctions |lijm of the total angular momentum operator J and its projection Jz. Each of these functions is a linear combination composed of products of the eigenfunctions

orbital angular momentum, that is, spherical functions Ylml (ÿ, ÿ),

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on the spin functions ÿimi . Here j, m are the quantum numbers of the total angular momentum and its projection onto the selected axis, l, ml are the numbers of the orbital momentum and its projection, i, mi are the same for the spin moment. The index i, the spin value, is fixed for each type of ion. The position of the index in the formula distinguishes it from the imaginary unit ÿÿ1. The eigenfunctions of H0 are equal, see, for example, [70, 122]

$$\|lijm = \sum_{mlmi} C^{jm}_{lml\,imi}\ Ylml\ÿimi\ , \qquad (4.121)$$

where the Clebsch-Gordan coefficients satisfy the orthogonality conditions
nationalities

$$\sum_{jm} C^{jm}_{lmlimi}\ C^{jm}_{lm_l\,im_i} = ÿmlm_l\ ÿmim_i \qquad (4.122)$$

$$\sum_{mlmi} C^{jm}_{lmlimi}\ C^{j_1m_1}_{lml\,imi} = ÿjj_1\ ÿmm_1$$

$$C^{jm}_{lmlimi} = 0 \text{ if } m = ml + mi\ .$$

From this we can find that the functions ‖lijm are also orthogonal, in particular, lijm‖lijm = ÿmm . This does not mean, however, that the interference term in the density p(ÿ0,t) is absent. To calculate the density
the probability of an ion at the point ÿ = ÿ0 , we write the state of the ion with the eigenfunction ‖lijm in a form that takes into account the dependence of the spherical functions on the angles and omitting for now the dependence on time, see (4.73):

$$ÿlijm = \frac{1}{ÿ2ÿ} \sum_{mlmi} C^{jm}_{lmlimi}\ ÿlml\ (ÿ)\ \exp(imlÿ)ÿimi\ . \qquad (4.123)$$

Here, the radial part of the wave functions is also omitted, which is not
has implications for the results of the section. The state of the ion after entering the capsule, generally speaking, is a superposition of functions ÿlijm with different weights for each possible set of indices. Therefore,
the density of the ion will include products with different sets. Three cases can be distinguished. The first is when the sets of indices
coincide. Such products create a contribution to the constant component of the density. This is the sum of the statistical weights of each of the states. The second case is when the sets of indices differ in their orbital l or total j momentum. These contributions to the density oscillate with
microwave frequency and do not play a role in the dynamics averaged over relatively large time interval of the order of 1/ÿc. The third case

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tea, - when the sets differ only in the value of the magnetic quantum number m of the projection of the total moment. Such products create
significant low-frequency fluctuations in ion density.

In order not to complicate the formulas, we will not write out the statistical weights of various states in this section, implying that the obtained dependencies should be averaged accordingly.
neny.

The probability density of an ion due to interference
states with quantum numbers m and m is equal to

$$p(ÿ0,t)= ÿlijm \rangle ÿlijmÿ = = \frac{1}{2ÿ} \sum_{mlmim\, lm\, i} Cjm\, lml\, imi\, Cjm\, lm_{li}\, im\, ÿlm_{l} \rangle ÿlml\, eiÿ0(mlÿm\, l)\, ÿim_{i} \rangle ÿimi .$$

The scalar product of spin functions dictates the condition $m_i = mi$.
Clebsch-Gordan coefficients $Cjm\, lml\, imi$ are different from zero at m = ml + mi, that is, in the last expression the summation is actually carried out over one index mi, since the others are defined by the ratio = m ÿ mi. Let us now take into account the $ÿÿÿ\, m\, i$ = mi, ml = m ÿ mi, m l factors,
determining the dependence of wave functions on time, then it is possible
write down:

$$2ÿ\ ÿ\ eiÿ0(mÿm\,) \frac{1}{} eÿi(ÿlijmÿÿlijm\,)t/ÿ\ p(ÿ0,t)= \qquad (4.124)$$

$$\sum_{mi} Cjm_{l(mÿmi)imi}\, Cjm_{l(mÿmi)imi}\, ÿl(mÿmi) \rangle ÿl(mÿmi) .$$

The contribution of the HM , diagonal in the facings $\|lijm$, is reduced
perturbation is only to the change in the energy levels of these states. It is known that that the difference in energy levels in the anomalous Zeeman effect is equal to

$$ÿlijm\ ÿ\ ÿlijm = ÿ(m\ ÿ\ m\,)gbHz ,$$

where g is the Lande multiplier for an ion with nuclear spin. In Section 6.2, the Lande multiplier is defined for some important biological ions.
If MP Hz is a function of time, and the matrix of the perturbation operator is diagonal, as in the case under consideration, then the product Hzt must be
replace with the integral Hz dt. Taking this into account, the probability density takes the form

$$p(ÿ0,t)= clijmm \exp im\ ÿ0 + gb \int Hz\, dt \qquad , \qquad (4.125)$$

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where the factor 1/2ÿ is included in the coefficient clijmm representing
the sum in the previous expression. In fact, the density (4.125) coincides with the
previously obtained expression (4.6), except that
that instead of the coefficient b in this section we have gb. Thus,
For the probability of dissociation, one can use the ready-made formula (4.19),
where the appropriate substitutions are made. In the coefficients ÿz = mÿ0/ÿ and
z = mÿ1/ÿ, one must use the new values
for the Larmor frequency ÿ0 = gbHDC and for the frequency associated
with an alternating field ÿ1 = gbHAC. It is convenient to keep the previous meaning
notations for Larmor frequencies, so wherever they appear in formulas we will
make the substitutions ÿ ÿ gÿ. We present the result for
contribution to the probability of dissociation due to mode interference
‖lijm and ‖lijm :

$$_{n}\frac{\sin 2A}{A2}J_{n}^{2}\left(\frac{m}{2}\frac{gh}{f}\right),\quad A=\left(\frac{m}{2}g+nf\right)\ddot{y}\ ,\qquad(4.126)$$

where all designations retain the meaning accepted in the book.

As can be seen, changes occur compared to spin-free ions.
both in the frequency and amplitude spectrum. Effective frequencies
follow from the equality A = 0:

$$f=\ddot{y}g\left(\frac{m}{2n}\right).\qquad(4.127)$$

Since the Lande factor g depends on the quantum numbers l and j, then
the frequency spectrum of dissociation is determined by the superposition of spectra
(4.126) determined by these numbers. The statistical weights of the corresponding
states are formed at the initial moment of entry of the ion
into the cavity and depend on many uncontrollable factors. Therefore, generally
speaking, the positions of the peaks also depend on the "biophysical
states" of the protein. The exception is the case of light ions, when
the width of the peaks is small and they practically do not overlap. In this case, it is natural
to expect the appearance of spectral peaks for each of the
allowed sets of quantum numbers.

Let us recall that for given orbital l and spin i moments
the total moment j can take values ‖l ÿ i‖ÿ j ÿ l + i, and its possible projections will
be numbers m = ±j, ±(jÿ1), ... Let us consider
More details about half-spin states.

When l = 0, the remaining quantum numbers are: ml = 0, j = 1/2,
m = ml + mi = mi = ±1/2. Substituting these values into (4.123) we find
functions that are orthogonal due to spin brackets

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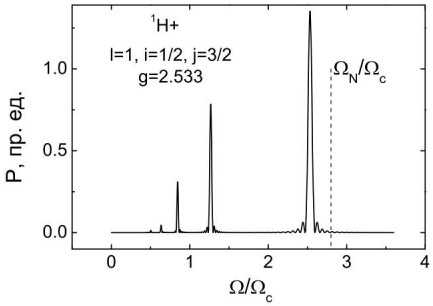


Fig. 4.27: Dissociation spectrum hydrogen complex in weak MP, h = 1.8; frequency of the main maximum less than the NMR frequency.

with respect to m. Consequently, they do not contribute to interference effects. These functions cannot create interference antinodes with respect to the angular variable at all, since they are independent of angles.

When l = 1, the projection ml = 0, ±1, and the possible values of the total moment will be the numbers j = 1/2 and j = 3/2. In the first case, the projection of the total moment takes on the values ±1/2. In this case, the numbers m and m in (4.124) can differ only by one. But then the brackets ÿl(mÿmi)ÿl(mÿmi) are equal to zero, since they are nonzero only for even values of the difference in magnetic numbers. Consequently, these states do not contribute to the interference.

States with l = 1, j = 3/2 provide non-zero values of the coefficient clijmm in (4.125) and lead to interference. The numbers m, m can take values ±3/2, ±1/2, then all non-zero brackets are the same: ÿÿ = ÿ1. Using the relationship between the coefficients
Clebsch-Gordan and Wigner 3j-symbols

$$C^{jm}_{j_1 m_1 j_2 m_2} = (\ddot{y}1)^{j_1 \ddot{y} j_2 + m_2 j} \sqrt{2j+1} \begin{pmatrix} j_1 & j_2 & j \\ m_1 & m_2 & \ddot{y}m \end{pmatrix},$$

and the formula for 3j-symbols in a special case, [122],

$$\begin{pmatrix} j_1 & j_2 & j_1 + j_2 \\ m_1 & m_2 & \ddot{y}m_1 \ddot{y} m_2 \end{pmatrix} = (\ddot{y}1)^{j_1 \ddot{y} j_2 + m_1 + m_2} \times$$

$$\times \frac{(2j_1)!(2j_2)!(j_1 + j_2 + m_1 + m_2)!(j_1 + j_2 \ddot{y} m_1 \ddot{y} m_2)!}{(2j_1 + 2j_2 + 1)!(j_1 + m_1)!(j_1 \ddot{y} m_1)!(j_2 + m_2)!(j_2 \ddot{y} m_2)!}^{1/2},$$

we can calculate $C^{3/2}_{1 \ddot{y} 1/2\ 1/2} = 1$, etc. The exact values of the coefficients c that can be found in this way are not important now. we.

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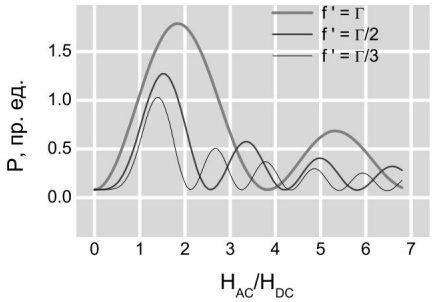


Fig. 4.28: Amplitude spectra hydrogen dissociation processes complex in weak MP on different frequencies.

Hydrogen

For a state with moments l = 1, j = 3/2, the Lande multiplier of the hydrogen ion, as follows from Appendix 6.2, is equal to 2.533. Figure 4.27 shows dissociation spectrum of a hydrogen complex. It is evident that the frequency of the main spectral dissociation peak is not equal to the proton NMR frequency. The amplitude spectra, as before, depend on the frequency at which they are fixed, Fig. 4.28. When calculating the spectra, equal weights of all admissible combinations m were used, ÿ = 50.

Potassium

States with l = 0, as was said above, do not interfere.
l =1 possible values of the total moment of a particle with spin 3/2 will be the numbers 1/2, 3/2, 5/2. The state with j = 1/2 is excluded for the same reasons. considerations that were given for a particle with spin 1/2.
The case j = 3/2 is also considered above; in the spectrum calculations it is only necessary to substitute the value of the g-factor for potassium, gjj=3/2 = 7.681. Case j = 5/2 gives new terms when summing (4.126) over m, m in which m = 4, and the g-factor is gjj=5/2 = 6.466. Calculation of frequency spectra for these states is shown in Fig. 4.29.

As can be seen, the main maxima occur at relative frequencies equal to the Lande factor. Note that, within the framework of the mechanism under consideration, the effect is absent at the NMR frequency of the ion.

Spectra for other values of angular momentum can be calculated similarly. The general conclusion is that the probable *effective dissociation frequencies of complexes with magnetic ions, in units* of ÿc, *coincide with the values of the factor Lande* for states starting with l = 1, j = 3/2.

■ Taking into account the spins of ion nuclei in interference effects provides rich possibilities.

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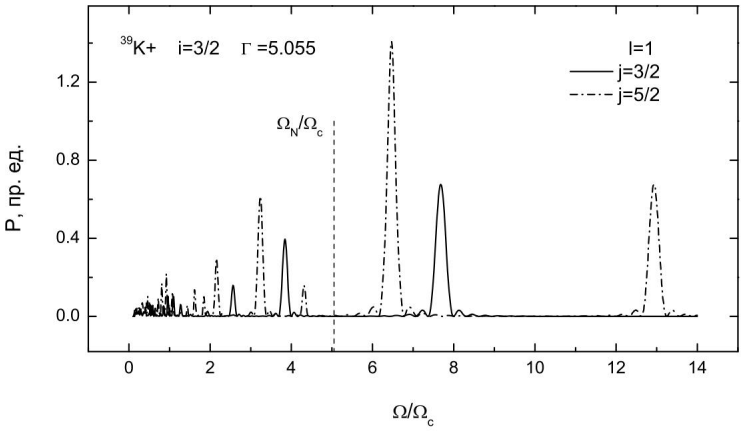


Fig. 4.29: Dissociation spectra of the potassium-protein complex in a uniaxial magnetic field, h = 1.8, ÿ = 10.

capabilities for identifying MP targets. Since for magnetic, that is, the position of the frequency spectral ions possessing spin peaks depends not on the charge-mass ratio, but on a more specific ion-isotope constant ÿ, the reliability of identification increases significantly. In addition, interference on magnetic ions gives qualitatively different behavior when moving from relatively weak to stronger magnetic fields, when the spin-orbit interaction becomes insignificant.

4.8.2 Alignment of spins in a uniaxial magnetic field field

Let's consider another, non-interference model taking into account spin ions. Suppose that the probability of some biochemical process depends on the spin state of the ion. This could be a biochemical reaction with proton transfer, for example, a photoprocess in bacteria. Spin states of tetrarhodopsin, see which will be discussed, are close in meaning states with a preferred // to polarization spin states, that is, direction of the spin "vector", see Appendix 6.3. For convenience, we will adopt the interpretation of quantum mechanics in which the uncertainty of non-commuting observables

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given is related to the measurement procedure, that is, we can talk about a vector whose components are simultaneously immeasurable. Let us recall that predictions of quantum mechanics regarding experimental observations quantities do not depend on the chosen interpretation, see, for example, Sudbury's monograph [683]. The presence of more than ten different interpretations of quantum mechanics reflects only attempts to construct its postulates in the most perfect way.

The formulas for the dependence of the process probability on the MP are similar to those which were obtained by considering the interference of angular orbital ion mode. The identity of both cases is seen in the constant magnetic field. In the previous model precessed the magnetic moment of the orbital movement of the ion, which meant rotation of the interference antinodes probability density of the ion. Now the spin magnetic precesses moment of the ion. The precession frequencies, of course, differ: ÿc/2 for the precession of the orbital magnetic moment and ÿN for the precession of the spin new magnetic moment.

As before, by imposing an additional parallel variable MP with certain parameters, it is possible to slow down precession. The magnetic moment will have one (polarization), two opposite (alignment), or several preferred directions. Accordingly, the spin of the particle acquires preferred directions. If the biochemical process proceeds in a certain

in accordance with the rules of selection by spin, which is a postulate of this model, then its speed will change.

For a proton in a uniaxial magnetic field Hz = HDC + HAC cos(ÿt) spin the Hamiltonian is equal to

$$H = \ddot{y}\ddot{y}IzH(t) ,$$

where ÿ is the gyromagnetic ratio of the proton. The Hamiltonian is diagonal in the matrix representation of the eigenfunctions ÿ1,ÿ2 of the operator Iz, therefore quantum transitions do not occur in these states. Average the value of the spin projection onto the z-axis is preserved. The other components of the spin "vector" experience oscillations. Let's find the spin projection on the x-axis, that is, Ix. The solution to the Pauli equation iÿÿ/ÿt = Hÿ is obtained by substituting into it the expansion ÿ= Izÿk = k ckÿk and using the equality Izÿk,

$$ck(t)= ck(0) \exp i\ddot{y}Ik \int_0^t Hz\, dt .$$

Here Ik are the eigenvalues of the spin projection operator. Next, we write, taking into account the action of the Pauli matrix ÿ1ÿm =

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ïym

$$Ix = \sum_k ck\ddot{y}k\,Ix \sum_m cm\ddot{y}m = \frac{1}{2} \sum_{km} c\ddot{y}\,kcm\ddot{y}k\ddot{j}\ddot{y}1\ddot{j}\ddot{y}m =$$

$$= \frac{1}{2} \sum_{km} c\ddot{y}\,kcm\ddot{y}k\overline{m} = 2\ \overline{1}\ (c\ddot{y}\,1c2 + c1c\ddot{y}\,2) .$$

Substituting the found expansion coefficients and denoting

$$c\ddot{y}\,1(0)c2(0) = c\,\exp(i) ,$$

we find

$$Ix = c\cos \ddot{y}Nt + h\sin(\ddot{y}t)\ \ddot{y}\ \frac{\ddot{y}N}{} \quad .$$

We omit the parameters c and y, which are irrelevant for the , which determine remainder of this paper. Obviously, the average value of the x-projection, as well as the y-projection, can be written as real and imaginary components:

$$Ix = \exp i\ \ddot{y}Nt + h\sin(\ddot{y}t)\ \ddot{y}\ \frac{\ddot{y}N}{} \qquad (4.128)$$

$$Iy = \exp i\ \ddot{y}Nt + h\ \ddot{y}\ \frac{\ddot{y}N}{}\sin(\ddot{y}t) \quad . \qquad (4.129)$$

It is now clear that the spin "vector" rotates or precesses non-uniformly. Under certain magnetic field parameters, it acquires preferred directions and relatively quickly switches between them. The rate of a spin-dependent biochemical reaction is hypothesized to change if the spin remains oriented in a certain direction for a sufficiently long time or if its orientation slowly changes, passing through this direction. The probability of such a situation occurring is determined by any of the components (4.128), for example, the x-component of the spin. As before, we write down a moving average over the interval T

$$Ix_T = \frac{1}{2\ddot{y}T} \int_{\ddot{y}(t\ddot{y}T)}^{\ddot{y}(t+T)} \ddot{y}N\ \ddot{y}N\ \ddot{y}\ \exp\frac{ih\sin}{}\ddot{y}\,d\ddot{y} \cdot \exp i\ \ddot{y}\ \ddot{y}\ \frac{}{}$$

It is similar to (4.9) with the difference that there is no summation over the indices of the magnetic quantum number, and the parameters take the values

$$z = h\ \ddot{y}\ \frac{\ddot{y}N}{}\ , \quad \ddot{y}z = \frac{\ddot{y}N}{\ddot{y}} \ .$$

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Therefore, using (4.12), we write

$$Ix_T = \sum_n \exp[i(\ddot{y}z + n)\ddot{y}T]\, A_n = \sum_n A_n \cos[(\ddot{y}z + n)\ddot{y}T],$$

Where

$$A_n = J_n(z)\frac{\sin[(\ddot{y}z + n)\ddot{y}T]}{(\ddot{y}z + n)\ddot{y}T}$$

Calculating the mean square of the last expression, which, according to the postulate is associated with the rate of biochemical reaction, we find

$$\overline{Ix_T^2} = \sum_n A_n^2 \overline{\cos 2[(\ddot{y}z + n)\ddot{y}T]} = \frac{1}{2}\sum_n A_n^2 .$$

It is taken into account here that the members of the product $Ix_T \cdot Ix_T$, containing somno-residents are cosines with different arguments, that is,

$$\cos[(\ddot{y}z + n)\ddot{y}T]\cos[(\ddot{y}z + n)\ddot{y}T], n = n$$

disappear upon final averaging over time.

Thus, for the desired probability we should write

$$P = \sum_n \left(\frac{\sin[(\ddot{y}z + n)\ddot{y}T]}{(\ddot{y}z + n)\ddot{y}T}\right)^2 J_n^2(z).$$

In dimensionless variables h = HAC/HDC and f =ÿ/ÿN, since (ÿz+ n)ÿT = (1 + fn)ÿ, the formula takes the form

$$P = \sum_n \left(\frac{\sin[(1 + fn)\ddot{y}]}{(1 + fn)\ddot{y}}\right)^2 J_n^2\left(\frac{h}{f}\right), \quad \ddot{y}=\ddot{y}NT. \quad (4.130)$$

Calculation result according to the scheme

h (1.8)f (0–1.3)ÿ(50)n(ÿ5–5)

is shown in Fig. 4.30. The height of the spectral peaks of the probability of quickly decreases with decreasing frequency due to the properties of Bessel functions, the form The curve does not depend on the initial conditions. The latter determine the relative magnitude of the magneto-dependent part of the reaction probability, which is maximum when the spin states are equally populated.

The amplitude spectra repeat those obtained earlier, Fig. 4.28. Frequency spectrum of a purely spin model

$$f_{max} \quad \ddot{y} \quad \frac{1}{n} \quad (4.131)$$

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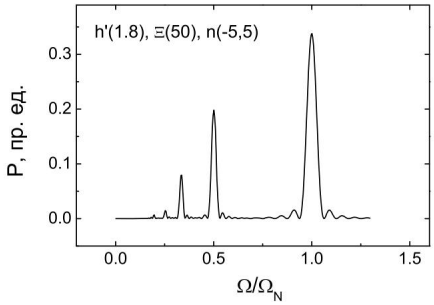


Fig. 4.30: Frequency spectrum reactions depending on its ve-probabilities from the spin state of the proton. Calculation by the formula (4.130).

differs from the dissociation spectrum of the hydrogen complex in the weak field approximation (4.127), since the position of the main peak exactly corresponds to the NMR frequency of the proton. This makes it possible to obtain experimental information about which of the two proposed spin
The mechanisms of the IBE are adequate to a particular situation.

4.9 Comparison of theoretical calculations with experiment

The pathway from a magnetic signal to a biological response is necessarily mediated by a multitude of factors at the biochemical and physiological levels. Due to the abundance and uncertainty of these factors,
they cannot be taken into account completely. Transformation of electromagnetic energy into a biological response can occur through several metabolic pathways simultaneously [283]. In addition, biosystems can
be sensitive even to such exotic factors as a temperature derivative of the order of 1 oC/hour, which leads to an MBE of the opposite sign [315].

This places limitations on the method of comparing experimental results and theory. Since the theory of magnetobiology
is aimed primarily at explaining the primary biophysical mechanisms of magnetic reception, its predictions are inevitably limited to the level of physicochemical processes. At the same time, predictions are almost always compared only with data from the biological level. As already mentioned, due to many unaccounted factors,
the connection between cause and effect here is ambiguous. Therefore, it is unlikely Is it justified to compare individual experimental points and even monotonous sections of curves with calculations? It is more correct to compare

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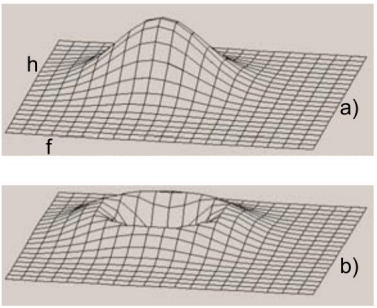


Fig. 4.31: Nonlinear transformation of extremal dependence bridges: a - dependence of concentration-enzyme C tractions on frequency f and the amplitude of the magnetic field h; b is the dependence of R(f, h) for a nonlinear response to the enzyme concentration. that.

to identify areas of dependencies that have extremes, and even then with reservations.

If the disturbances caused by the magnetic field at the level of biophysical structures are in some sense small, then a linear approximation for multi-level nonlinear system linking these disturbances with a measurable biological response. Extreme dependence in In this case, the biophysical response to the magnetic field will cause a similar extreme dependence of the bioreaction to the magnetic field. This makes it possible to compare experiment and theoretical predictions regarding *the magnetic conditions* for the occurrence of extremes, that is, the magnetic field parameters that ensure extreme MBE.

In the general case, a significantly nonlinear response of a biological system to changes at the level of biophysical structures is possible, when one extremum at the biophysical level corresponds to several extrema of the biological reaction R. Figure 4.31 shows an illustration showing how two maximums emerge from one maximum.

Relationships of the type shown in Fig. 4.31–b are measured very rarely [527], so the linear approximation is most often quite justified.

■ Since the correct criterion for the correspondence between theory and experiment is in magnetobiology there is a coincidence of experimental and calculated *conditions* the appearance of reaction peaks, then all forms of the calculated dependencies obtained by shifting and scaling along the Y axis should be considered equivalent. Further, when comparing the results, it is assumed that transformation of theoretical curves or experimental data was carried out in order to obtain the best visual match.

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4.9.1 Frequency spectra

In [245] Alipov and Belyaev investigated the biological response of cells *E. coli* K12 AB1157 for combined MP according to scheme 9

$$B(43 \pm 1)b(30)f(6–69)Bp(19 \pm 1)\ .$$

Maxima were found at frequencies of 8.9; 15.5; 29.4; 62 Hz. There is also an unexpressed maximum at a frequency of 44 Hz.

Calculations using formula (4.23) were carried out for the 40Ca2+ ion. The above-mentioned values of the HAC,HDC fields were used. The perpendicular component was not taken into account due to a special study [277]. The period of moving averaging approximately corresponds to the dissociation constant of the Ca-calmodulin complex: T = 0.1 s. The cyclotron frequency is fc = 32.9 Hz. The best agreement between the relative peak heights in theory and experiment is obtained with the following values of the density matrix elements: amm = 1, m = 1, 2;

amm =0.5, m =3; amm =4, m =4.

The calculated curve and experimental data [245], adapted to the dimensionless frequency, are shown in Fig. 4.32. It is clear that there is satisfactory agreement between theory and experiment for all maxima, as
to the left and right of the cyclotron frequency fc.

It is noticeable that the experimental peaks are slightly shifted to the side low frequencies in relation to theoretical values. Such a "red" shift of the MBE maxima may be due to the loss of part of the charge by the ion as a result of its binding. Indeed, any
chemical bonding, including relatively weak ionic bonding,
involves a displacement or attraction of the outer electron cloud of the ligand toward the ion—the cation. As a result, the effective charge of the ion q decreases. Since the frequencies of the MBE peaks are proportional
ÿc = qH/Mc, this means their red shift.

The perpendicular component of the constant magnetic field, as follows from sections 4.4 and 4.5, does not matter for rotating complexes.
If we assume that this MBE was caused by the reaction of stationary complexes, then to determine the cyclotron frequencies we must take
the modulus of the magnetic field vector, in this case it is 47 ÿT. Then the most suitable ions are Mg, fc = 59.3 Hz, and Na, fc = 31.4 Hz.
The calculation for Na is shown in Fig. 4.32. As can be seen, identifying the ion targets is difficult. It is possible that different types of ions, as well as rotating complexes, are involved in the formation of this spectrum.

9See magnetic condition notations on page 57.

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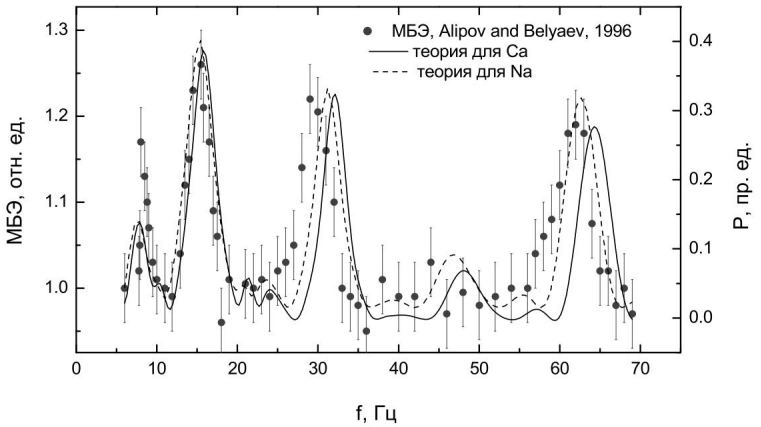


Fig. 4.32: Interference spectra according to formula (4.23) for calcium and sodium ions and experimental data [245, 276] on the change in viscosity of the *E. coli* cell suspension in a combined magnetic field.

The frequency spectrum of MBE on neoblast cells of regenerating planarians was studied by Lednev, Srebnitskaya et al. at frequencies close to the NMR frequency of hydrogen atoms [179] and in the range of cyclotron frequencies of calcium 40Ca and magnesium 24Mg ions [129]. The following experimental scheme was used for hydrogen

B(42.74 ± 0.01)b(78.6 ± 0.8)f(1808–1830/ ÿ 3) .

The frequency dependence of the resonance type with a maximum at the proton NMR frequency and a width of about 10 Hz is shown in Fig. 4.33 in the form of several experimental points. The theoretical curve was calculated using formula (4.130) for |n|ÿ 3 and within the limits of experimental accuracy.

The ment coincides with the experimental data.

To measure spectra near cyclotron frequencies, we chose schemes

B(20.9 ± 0.1)b(38.4 ± 0.1)f(12–20)T (11 ± 0.5o C)

for calcium and

B(20.9 ± 0.1)b(38.4 ± 0.1)f(20.4–32.4)T (10.5 ± 0.5o C)

for magnesium. Figures 4.34 and 4.35 show the results of measurements of the mitotic index of cells and calculations using the ionic interference formula.

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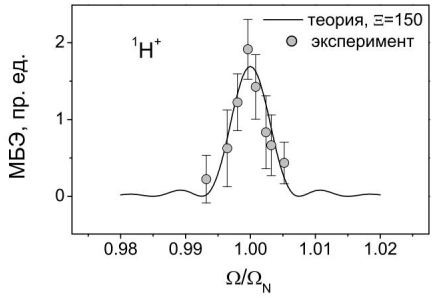


Fig. 4.33: Comparison of the calculated, formula (4.130), and experimental [179] frequency spectra of the MBE near the NMR frequency of 1H protons in a uniaxial magnetic field.

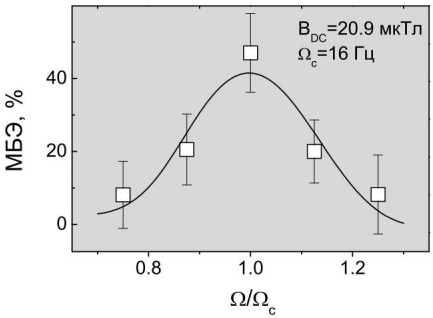


Fig. 4.34: Experimental data on MBE on planarians [129] near the cyclotron frequency of calcium ions 40Ca and the curve calculated using the ion interference formula.

rations. The best agreement was obtained by taking into account the interference of levels m = ±1 and the coupling parameter T = 0.09 s for calcium, which is consistent with the value T = 0.1 s found by comparing theoretical calculations with the data [245]. For magnesium, the best value of the coupling parameter was T = 0.06 s.

In [615], Prato, Carson et al. presented the frequency spectrum of the MBE on the land snail, measured under the conditions B(78.1)b(141)f(10–240). The spectrum is polyextreme and therefore suitable for comparison with the theoretical calculation. The calculation was made for the calcium ion 40Ca according to the scheme

h (1.8)f (0–4.3/0.02)ÿ(27)m(ÿ4–4)n(ÿ3–3)a(1) .

The results of the data superposition are shown in Figure 4.36 and, overall, are consistent. It is noticeable that the experimental data detail here is insufficient for reliable identification of the spectral peaks.

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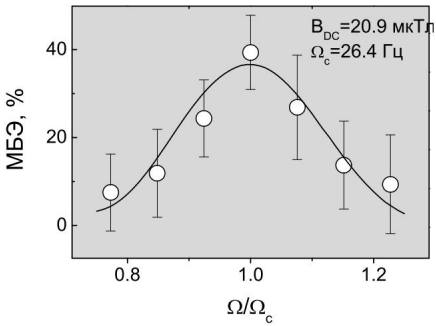


Fig. 4.35: Experimental data [129] and the corresponding theoretical curve near the cyclotron frequency of magnesium 24Mg.

4.9.2 Amplitude spectra

Libow, Rozek et al. [332] investigated the incorporation of a tracer, a calcium isotope 45Ca, in human lymphocytes under the combined action of parallel constant and alternating magnetic fields. The experimental design was chosen taking into account the expected tuning to the cyclotron frequency of this calcium isotope.

B(21)b(0–220)f(14.3) .

The authors observed a significant increase in the MBE at b ÿ 28 ÿT.

The theoretical curve was calculated using formula (4.23) in the range of change of the relative amplitude h = 0–11 at the cyclotron frequency, f = 1. All matrix elements were chosen equal to unity. Interference of states with magnetic quantum numbers no greater than two was taken into account. Experimental data [332] were presented as a function of the dimensionless relative amplitude and are combined with the theoretical curve on one graph, Fig. 4.37. It is clear that the experimental points are in good agreement with crooked.

Fibroblast cell proliferation in combined AC–DC The field was investigated by Ross in [642]. They varied both the amplitude of the variable, and the magnitude of the constant magnetic field vertically. The horizontal component of the external local magnetic field was not controlled. Since the experiments were carried out in a five-layer steel incubator, it can be assumed that the external field was significantly reduced. The points of the amplitude spectrum are plotted on the graph in Fig. 4.37 with optimal scaling and shifting and show more or less satisfactory agreement with the calculated crooked.

The dependence on the value of the constant MP is shown in Fig. 4.38 together with the calculated curve under the same magnetic conditions. It is evident that

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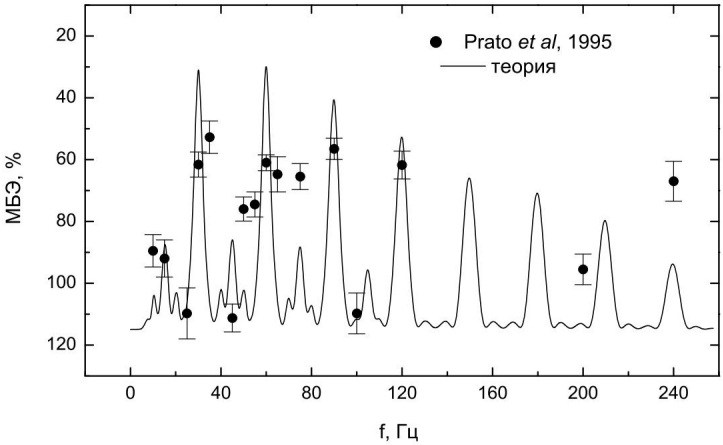


Fig. 4.36: Combination of the calculated frequency spectrum for the calcium ion and experimental data [615] on the MBE on the land snail in the MP HDC = 78.1 ÿT, HAC = 141 ÿT.

calculation using a frequency different from the experimental one, already does not give a good match.

Experiments by Prato, Cavaliers et al. [546] according to the scheme

B(78)b(18–547)f(60)Bp(±0.8)n(8–31)

were performed for comparison with the predictions of the formula proposed in [519]. Good agreement could not be achieved. These data later adapted by Blanchard, House and Blackman [321], where they compared the degree of correspondence between the calculations according to Lednev's recipe and according to Blackman's recipe [320] They showed that neither formula is capable of predicting the resulting dependence.

Figure 4.39 shows the data [546] and the calculation using the ion interference formula. It is clear that theory and experiment agree satisfactorily. Later, Prato, Cavaliers, and Thomas [616] reported reproducing these results under conditions

B(78.1)f(60)b(< 0.2, 141, 299, 414)n(ÿ 25) .

These data are also consistent with the theoretical calculation, although in to a lesser extent, Fig. 4.40.

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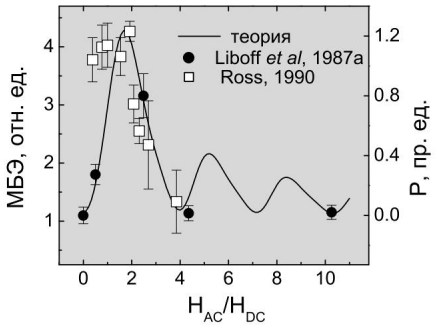


Fig. 4.37: Comparison of theoretical interference spectrum and experimental data [332] on the introduction of a calcium label into human lymphocytes.

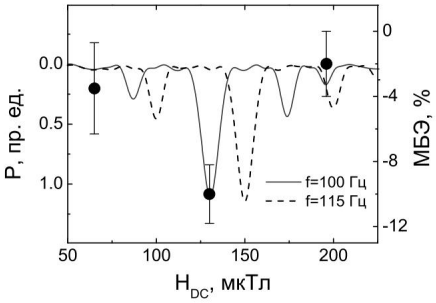


Fig. 4.38: Proliferation of fibroblast cells at an amplitude of MP 250 ÿT and frequency 100 Hz alternating MP (MBE), according to data [642]. Calculation for 40Ca ions in those same conditions (P).

The ion interference model predicts the independence of the MBE from the simultaneous proportional change of HDC, HAC, f, obviously, while the relative frequency f and amplitude h remain unchanged. This is precisely what was tested in the experiments of Prato, Cavaliers and etc. [530]. The authors conducted experiments according to the scheme

B(39 k)b(70.5 k)f(30 k)n(ÿ 33)k(1, 2, 4)

with snails exposed to a magnetic field in the dark and in the light. There were six experiments in total: three magnetic field conditions, two illumination conditions, and six control experiments, which differed in value.
b(0 ± 0.2). Magnetic conditions corresponded to the cyclotron frequency calcium ions 40Ca. The results are presented in Fig. 4.41 and do not contradict the model predictions.

In discussing the experimental data of Garcia-Sancho, Montero et al. [398] on the effect of magnetic fields on the capture of the radioactive label 42K in Ehrlich cancer cells and human leukemia cells it was indicated that they are suitable for comparison with theoretical calculations. Indeed, The MP configuration used corresponds to that considered in the basic model of interference of bound ions. Although the proteins responsible

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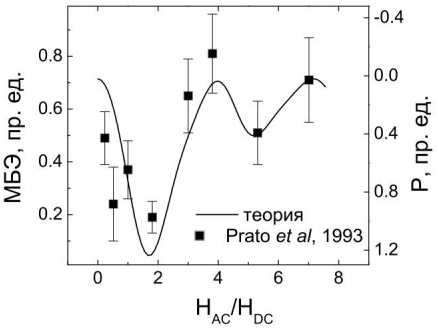


Fig. 4.39: Comparison of experimental data [546] with calculations using the interference model formula.

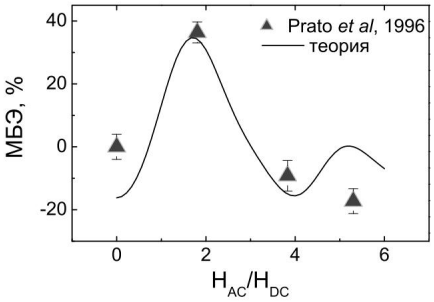


Fig. 4.40: Experimental data [616] on MBE on land snails when setting up to the cyclotron frequency of calcium 40Ca and theoretical curve.

Since the molecules responsible for potassium binding, their structure and biochemical role are unclear, it made sense, given the possible commonality of molecular interference processes, to compare the model's predictions with experimental data. For this, a formula for dimensionless variables was used
(4.23) with the substitution of parameters corresponding to the experiment. All the elements of the density matrix were assumed to be equal to one. Let us recall, that the relative heights of the various interference maxima depend on them. Since a single extremum was observed in this experiment, the choice of values for the density matrix elements is generally unimportant. The comparison results are shown in Figures 4.42

where the calculation is carried out according to the schemes

B(0.41)b(1.41)Bp(ÿ 0)f(13.5–16.5/1)n(8–24)

B(0.41)b(0.71, 1.41, 2.82, 14.1)Bp(ÿ 0)f(14.5, 15.5)n(8–24)

for frequency and amplitude spectra, respectively.

Here, the agreement between experiment and theory is rather conditional, especially in the case of comparing the amplitude dependences of the MBE.
At the same time, there is no sharp contradiction, since the motive of the drawings Overall, it's the same. The number of experimental points is insufficient.

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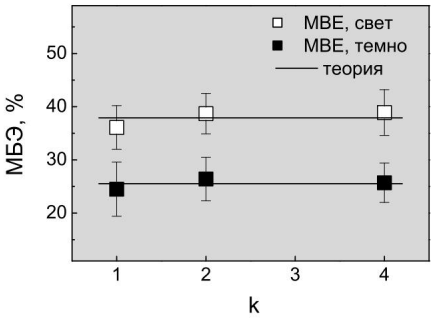


Fig. 4.41: Constancy of the MBE with a simultaneous proportional, k-fold, change in the MP parameters. Experimental data [530].

to extract any additional information. Note that
The authors of [398] also reported observing the effect with perpendicular orientation of magnetic fields, which is commented on in section 4.4.

In [179] Lednev, Srebnitskaya et al. measured the amplitude spectrum of the MBE in addition to the frequency spectrum. The experimental design B(20.87 ± 0.01)b(0–80/ ÿ 20)f(889) was chosen so as to obtain the amplitude dependence at the frequency ÿN for hydrogen atoms. The amplitude dependence had a maximum at a ratio of the amplitude of the alternating to the magnitude of the constant field of 1.8, Fig. 4.43. There is good agreement with
theoretical curve calculated using the ion interference formula (4.130), |n|ÿ 3, with the MF parameters corresponding to the experiment.
The description of the experiment is given in the overview section.

On planarians, amplitude spectra were also obtained [129] on the cycle lotron frequencies corresponding to calcium and magnesium ions

Ca	B(10.4 ± 0.1)h (0–3.6)f(8.0 ± 0.1)
Mg	B(20.9 ± 0.1)h (0–3.8)f(26.4 ± 0.1) .

Fig. 4.44 shows the experimental points as well as the theoretical curve according to the ion interference model. Here too there is convincing entral consent.

4.9.3 Spectra of rotating complexes

Theoretical analysis and experimental data show that the amplitude spectra of the MBE by the ion interference mechanism are practically
are independent of the type of ions involved in magnetoreception. This allows for comparison of data obtained in different biological systems.

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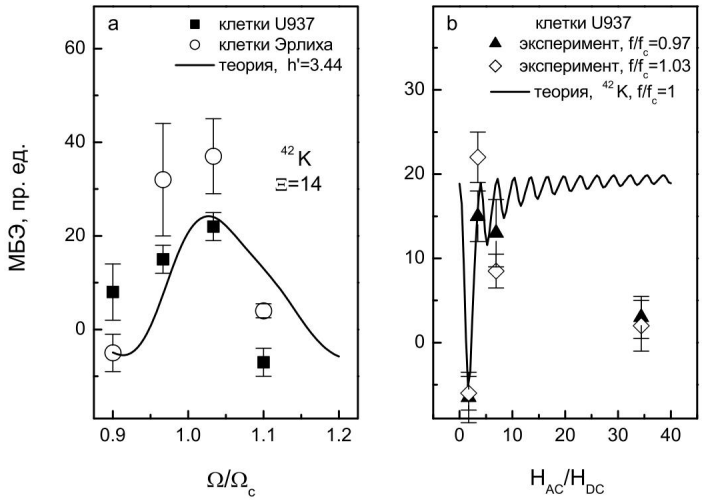


Fig. 4.42: Comparison of data [398] with calculation using formula (4.23) for 42K+ ion : a — frequency spectrum, b — amplitude spectrum of the interference tions of bound ions.

with the same theoretical dependence. Within 10% accuracy, this dependence is determined by the function J2 1(h). At the same time, as
It was shown in section 4.5 that for rotating complexes the shape of the amplitude spectra depends on the type of ions. In the particular case when
the relations are fulfilled

$$ÿ = ÿ1/2 ± 1/4 \ ,f = 1/2 \ , \qquad (4.132)$$

where ÿ is the relative rotation frequency, the amplitude spectra are close to the specified function of the doubled argument, J2 1(2h). The experimental conditions in the works of Blackman et al. [421, 488], where similar spectra were observed, almost exactly satisfy these conditions if we assume that lithium ions Li+ bound to proteins rotating at a speed of 18 or 63 rpm are involved in magnetoreception. Suitable
less, but magnesium ions Mg2+ on proteins rotating at 8.1 or 38.1 rpm are also acceptable. These ions, as well as lithium ions,
discussed in the cited works [421, 488] as possible targets
AC–DC MP.

Interestingly, the amplitude spectra of any other ions at any other rotation speeds were far from agreeing with the experiment.

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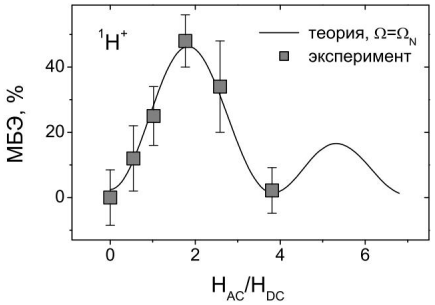


Fig. 4.43: Theoretical amplitude spectrum according to the formula (4.130) and experimental spectrum [179] at NMR frequency proton.

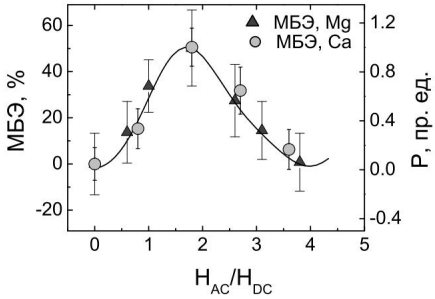


Fig. 4.44: Data comparison [129] on MBE in regenerating planarians at a cyclotron frequency of calcium 40Ca and magnesium 24Mg.

ment. The spectra calculated using formula (4.87) are presented in Fig. 4.45 together with adapted experimental data. The figure uses the argument ÿh , where the coefficient ÿ allows one to use a single curve J2 1(ÿh) for both stationary and rotating complexes. For the latter, the coefficient ÿ is specified, which limits the suitable ion type and the rotational speed of the complex.

Note that comparison of the predictions of ion interference in perpendicular magnetic fields with experiments [387] (see Section 4.4) also pointed to lithium ions as a probable target of magnetic fields in MBE on nerve cells. PC-12 cells.

Trillo, Ubeda, et al. [551] and Blackman, Blanchard, et al. [374] performed experiments on these cells, also shown in Fig. 4.45, in MP tuned to the cyclotron frequency of the hydrogen ion H+. Approximation of these data is possible if the MP excites interference states with magnetic quantum numbers differing by four, m = 4. The argument of the Bessel function J1 should be equal to ±2h to obtain agreement. On the other hand, the relative frequency f is equal to unity, as in the experiment. This requires the equality m = ±4, see (4.90). Then we obtain the same as (4.132), the relation for the angular

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Table 4.1: Parameters of the spectra of rotating complexes†

Ion H, ÿT fc, Hz f = m ÿ			f /fc			frot = ÿ ÿ/2ÿ	
H+	2.96	45.05	1	4	-0.25	11.25	-2
H+	2.96	45.05	-1	4	-0.75	-33.8	2
Li+	36.6	81	0.556	2	-0.222	18	-1.8
Li+	36.6	81	-0.556	2	-0.778	-63	1.8
Mg2+	36.6	46.2	0.975	3	-0.175	8.1	
Mg2+	36.6	46.2	-0.975	3	-0.825	-38.1	

†The MF frequency f = ÿ/2ÿ was equal to 45 Hz in all cases, as in the experiments [421, 488, 551, 374]. The angular velocity ÿ ÿ ÿ/2ÿfc for Li ions was calculated with the best visual fit between the curve and experimental data, that is, ÿ = ÿ 1+ ÿÿ1 /2 at ÿ = ±1.8. The sign f denotes right or left rotation with respect to the direction of the magnetic field.

speed: ÿ = ÿ1/2 ± 1/4. All parameters and basic quantities for Spectrum calculations are given in Table 4.1.

The spectrum calculated using formula (4.87) for the hydrogen ion H+ with the parameters indicated in the table coincides with the similar spectrum for lithium ions Li+ and shows good agreement with the experiment, except for a narrow range in the center of the peak in Fig. 4.45. Sharp The decline in the MBE at the center of the maximum is not explained within the framework of the mechanism under discussion. In [374], it was suggested that different mechanisms or different H+-binding sites acting in opposite directions could be responsible for this.

4.9.4 Pulsed magnetic field

The effect of the MF pulse sequence on the rate of gene transcription was studied by Aarholt, Flynn, and Smith in [229]. A polyextreme dependence of the rate on the magnitude of rectangular MF pulses in the range of 200–660 ÿT at a repetition frequency of 50 Hz was found. The authors believed that the transcription rate was influenced by a suppressor protein that inhibits synthesis; in turn, the activity

The activity of this protein was controlled by a magnetic field.

The paper did not report the magnitude and direction of the local constant magnetic field and the pulse duration. For comparison with the calculation

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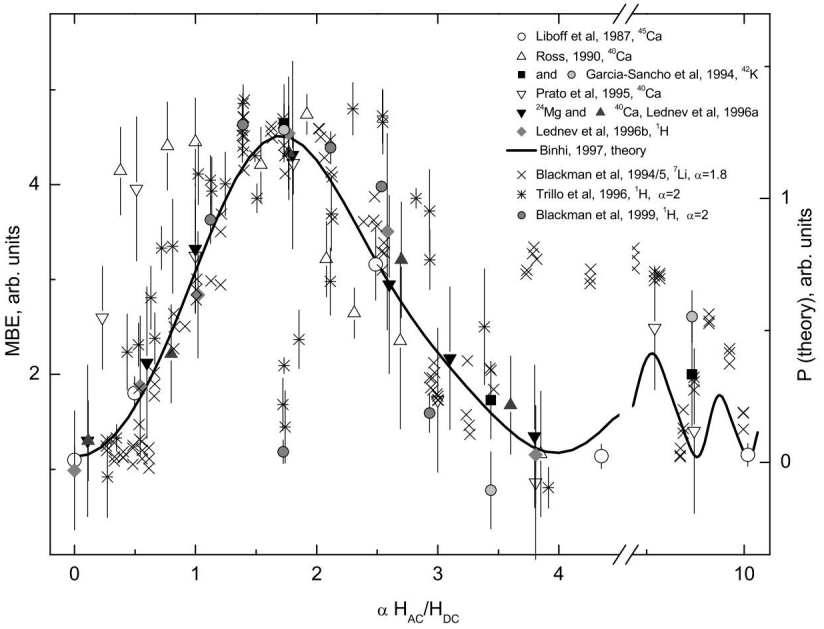


Fig. 4.45: Experimental data [332, 642, 421, 398, 488, 615, 179, 129, 551, 374] according to the MBE in a uniaxial MF (in [642] a weak perpendicular component of a constant MF is noted). The theoretical amplitude The spectrum (line) is calculated for fixed ion-protein complexes (the coefficient ÿ = 1 is not specified), as well as for rotating complexes (the value of ÿ is indicated).

In the formula of interference in pulsed fields, the constant field was chosen to be parallel to the variable field and equal to the average value of the geomagnetic field. thread field.

The experimental data shown in Fig. 4.46 show two multidirectional extremes in the action of the magnetic field. The interference mechanism for any one type of ion-protein complexes predicts a unidirectional change in the biological response for all amplitude-frequency windows of the MP. At the same time, there are data about the multidirectional, opposite action of the MP in different windows. In [378] it was reported that MF with a frequency of 16 Hz caused an increase activity of the enolase enzyme by 60%, and the 60 Hz field decreases

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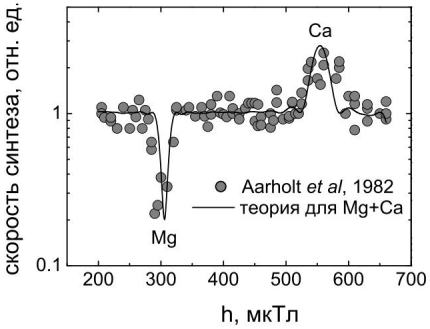


Fig. 4.46: Data [229] on the rate of gene transcription in *E. coli* in pulse MP and calculation by formula. The weighted the sum of the curves for the ions of the magnet- tion and calcium.

activity decreased by 25% compared to the control level. In [398] also observed opposite effects of 42K isotope uptake in some cancer cells when changing the frequency or amplitude of the variable component of the MP. In [564] a similar multidirectional action of the MP This was attributed to the fact that the magnetic field's targets could be different ions, causing opposite bioeffects. This idea of ions competing for the sign of the effect was subsequently shared by other authors.

In the case under consideration, the author in [296] suggested that oppositely directed extrema of the MBE of the pulsed MF are also formed by the responses of different ions, calcium and magnesium, since they can compete for binding sites. The calculation was carried out according to the same scheme for both types of ions

H(50)f(50)h(200–660)ÿ(0.013)T (0.2)m(ÿ1–1)r(ÿ2–2)

according to formula (4.45). The sum of the dependencies for both ions for the best fit with the experimental curve was taken with weights of -0.5 for Mg and 1.3 for Sa. Fig. 4.46 shows the result of superimposing experimental points and the calculated curve.

Change in the surface negative charge of human cells U937 by 14%, P = 0.03, in pulsed MP was observed in [248] Smith, Goodman et al. The pulse sequence consisted of pulse trains with a frequency of f = 25 Hz. Each train contained N = 22 sawtooth pulse with amplitude h = 630 ÿT, front front ÿ1 = 200 ÿs and trailing edge ÿ2 = 20 ÿs. In this case, the entire packet can be considered as one impulse, since the interval between in packs significantly longer than the duration of the pack. The "area" of such of the composite momentum is equal to ÿ = Nh(ÿ1 + ÿ2)/2. Data on the magnitude of the constant MF were not given, so agreement with the theory could consist in the consistency of the calculated HDC values from the rule

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highs (4.40)

$$\ddot{y} = \frac{1}{b}\,\frac{2\ddot{y}r}{m}\cdot\frac{HDC}{f}.$$

It is easy to verify that by selecting integer coefficients in relatively narrow intervals r ÿ [ÿ1, 1], m ÿ [ÿ1, 1], one can find such HDC values from the most probable range (ÿ50, 50) ÿT,

that rule (4.40) will be exactly fulfilled for ions from the series Ca, Mg, K, Na, b = 241, 394, 123, 210 respectively. Thus, for the main maximum r = 0 we find HDC = ÿ38.1 ÿT (the sign indicates the direction) for all ions; recall that rule (4.40) at r = 0 corresponds to mutual compensation of the local constant field and the constant component of the pulse sequence and therefore does not depend on type of ions. For the maximum r = 1, m = 1, HDC = 36.7 ÿT for ions sodium and HDC = 27.1 ÿT for calcium, etc. Thus, the predictions of the interference mechanism of bound ions in pulsed MF are not contradict the results of the experiment [248].

The data obtained by Mooney, Smith and Watson [578] also do not contradict the interference mechanism. They stimulated the blastogenic activity of mononuclear blood cells with the drug phytohemoglutenin. It turned out that 72 hours of exposure to 3 Hz pulses

MF of magnitude h ÿ 4.5 mT and duration ÿ ÿ 5 ms statistically significantly reduced the yield of labeled thymidine by 20%. The local MF parameters were not specified, but the product fÿh ÿ 60 ÿT corresponded overall to the range of pulsed ion interference. At the same time, at the same time, the maximum electric field induced by the pulse themselves amounted to about 23 mV/m, according to the authors' estimates. This does not exclude and another MBE mechanism, in particular, utilizing the form of interference in a low-frequency electric field, see section 4.6.

4.9.5 Constant magnetic field and magnetic vacuum

Experimental data of Lednev, Srebnitskaya et al. [129] on growth proliferative activity in regenerating planarians with a decrease in the constant magnetic field to the level of its geomagnetic daily variations together with the calculated curves are shown in Fig. 4.47. Naturally, full compensation for MP could lead to a response from all ions involved in magnetosensitive ionic binding processes. Zeeman splitting of the levels disappears in zero magnetic field.

for all particles at once. In this case, the contributions of different ions to the measured In practice, the quantities may have different signs. It is difficult to separate the contributions.

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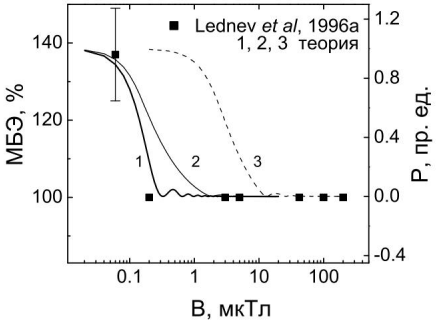


Fig. 4.47: Theoretical curves in constant magnetic field for H+ — 1,2, Ca2+ — 3 and MBE according to data [129]. Curve 1 is only a spi- new dynamics of hydrogen ions H+.

Some information about which ions determine biological response in a near-zero MP, gives the width of the maximum on the dependence MBE on the field strength. Figure 4.47 shows the curves calculated using formula (4.87), ÿ=0, for different ions, calcium 40Ca and hydrogen 1H.

The calculation used data on the value of the characteristic time of connection T, obtained from the best fit of theoretical frequency spectra with data from other experiments. For calcium T = 0.1 s [245], for hydrogen T = 0.036 s [179]. Since hydrogen, unlike calcium, has a nuclear magnetic moment, the following values were found for it:
Two curves were calculated, 1 and 2. The first one differs in that only the spin dynamics were taken into account. This made sense, since the corresponding value of T was obtained from a comparison with experiment,
where only spin effects were significant. As can be seen from the figure, the best fit is given by the assumption of hydrogen-dependent processes in zero magnetic field. In [129] it is assumed that the contributions of other ions in regenerating planarians, calcium, magnesium and potassium, in the zero field mutually compensated. The role of the orbital angular states of hydrogen needs to be clarified based on experimental data using magnetic resonance frequencies corresponding to the cyclotron frequency of the proton.

The data of Belyaev, Matronchik and Alipov [277] on the change in viscosity of a suspension of lysed *E. coli* cells after exposure to a constant magnetic field, together with the calculation using formula (4.87), are presented in Fig. 4.48.
The calculation was performed under the assumption that the experimental curve is a superposition of responses from different ions. Different ones were tested biologically important ions, Li, K, Na, Mg, Ca, Zn. In the work [303] the author, Alipov and Belyaev showed that a satisfactory approximation can be achieved only with a unique superposition of the contributions of magnesium, calcium and zinc ions at the same angular velocity

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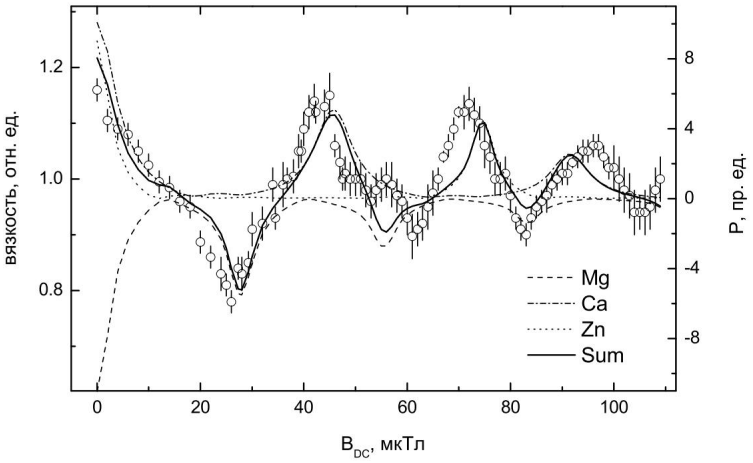


Fig. 4.48: Approximation of experimental data on MBE on *E. coli* cells in a constant magnetic field with calculation using the interference formula
Mg2+, Ca2+, Zn2+ ions associated with the protein complex in rotation
in a solid state.

ion-protein complexes

$$Psum = ÿPMg + PCa + PZn . \qquad (4.133)$$

The contribution of each of these ions was necessary. In Fig. 4.48 they are also shown separately. The reaction time T corresponding to these
T = 0.1 s was chosen for the ions of the complexes. Other calculation details:
m| < 3, |k| < 5, a =1, c2 $_k$ =0.5|k| . | The important thing is that the angular parameter
the speed of ion-protein complexes for all ion-proteins was the same, ÿ = 110 sÿ1, which corresponds to a rotation speed of 18 rpm. At
Under this condition, it was possible to find a single, unique combination ions, Mg, Ca and Zn, which provided satisfactory compliance.
For other values of ÿ, suitable ion combinations were not available.

If the types of ion-protein complexes and the direction of their action are fixed, that is, magnesium is opposite to calcium, and zinc is in the same direction with calcium, then only one parameter, ÿ, remains for fitting the calculated and observed positions of the extrema. Relative
The amplitudes of the peaks cannot be predicted by physical mechanisms; they are determined by the corresponding biochemical kinetics. Therefore, the relative weights of the ion contributions (which turned out to be the same) and

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the width of their peaks, that is, the T time of , were selected for fitting the entire
the curve as a whole, only to emphasize the expressiveness of the correspondence. It is
interesting that the times of conformational reactions for calcium
and magnesium coincided with the previously used values, and even some minor details of
the shape of the measured peaks were reflected in the calculation. It should be noted that a
mathematical approximation of the polyextremal curve would require varying several
parameters,
by the number of extrema. Apparently, the good agreement between the calculated and
measured positions of the extrema, achieved by varying just one parameter, the speed of
rotation of the complexes, is a consequence of the assumption that it is the rotating complexes
that are involved in magnetoreception.
complexes.

■ In [303] it was suggested that the probable common carrier of the indicated ion-protein
complexes is DNA in the process of transcription. The speed of this process is about 40
nucleotides per second.
accompanied by the rotation of some proteins, in particular RNA polymerase, around DNA
[381]. It is known that each molecule of RNA polymerase in *E. coli* cells binds two zinc atoms
[682]. In these
In some places, zinc ions can be replaced by magnesium and other divalent ions [596], which
changes the activity of the protein and leads to changes in the rate of the process. Since the
period of the DNA helix is 10
base pairs, then the expected rotation speed is 4 rpm, which
does not contradict, in order of magnitude, the found rotation speed
18 rpm. Thus, the rate of protein rotation during transcription may be one of the important
parameters of this process, determining its response to magnetic resonance. Note the
coincidence of this rate with the possible rotation rate of Li-protein complexes in PC-12 cells,
found above from a comparison of the amplitude spectra.

A classic example of other biomolecular rotations is
flagellar motor and ATPase [371].

4.9.6 Electric field spectrum

The scatter of experimental data on the biological effects of EP
significantly higher than in similar experiments with magnetic fields. This is probably due to
the fact that in the case of EP, there are poorly predictable random constant microscopic EP
gradients that affect the position of spectral peaks. Microscopic magnetic fields are generated
only by magnetic moments.

nuclei of atoms; but the region inside the capsule is relatively far from the water-

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environment with protons emitting magnetic fields, and the nuclei of ligands, such as 16O, non-magnetic.

Below is a summary of the results of two groups of experiments, depending on the method of applying the EP to biological tissue, the approximate windows of the EP parameters in which statistically observed
reliable biological effect.

In the first group of experiments, samples were placed between plates capacitor, without direct electrical contact. In [266] Bowen and Eidi determined the rate of 45Ca ion outflow from a pre-ion-enriched chicken brain tissue under EP exposure. A 15% decrease in calcium output was observed with EP parameters in range of 3–24 Hz, 10–60 V/m. Fitzsimmons, Farley et al. reported that bone cell culture increased the proliferation rate by 50% under the influence of a field of 12-20 Hz, 430 V/m, [440]. Nazar, Paul and Dutta [585] observed a decrease in the specific activity of the enzyme enolase by 20% in a field of 10–70 Hz, 65 V/m. In all experiments, the response of the biological system was measured at only a few parameter values. Therefore, it is difficult to relate the data to the behavior of any smooth curve. However, a general conclusion can be drawn that in these In experiments, the window of EP activity is associated with low-frequency range of 10–100 Hz and EP intensities of 10–100 V/m, in order quantities.

In the second group of experiments, EP in the environment was created by means of electrodes immersed in the medium. In this case, the current in the circuit was measured, and the magnitude of the EP could be calculated from the voltage drop across additional measuring electrodes. MacLeod, Lee and Ehrlich [565] observed a 30% decrease in the rate of DNA synthesis in a collagen matrix with embedded fibroblast cells under the influence of EP 1–10 Hz at a current density > 1 ÿA/cm2. Blank and Soo [323] recorded a 15% decrease in Na,K-ATPase activity in a special suspensions of enzyme with substrate under conditions of 20–1000 Hz, > 70 ÿA/cm2. Blank, Soo et al. [339] measured a 30% increase in transcription rate in HL-60 cell culture at 60 Hz, 0.3–3 ÿA/cm2. Goldman and Pollack [450], Cheng and Goldman [340] also observed a 60% change in the rate of DNA synthesis in a collagen matrix with human fibroblasts in the 10–100 Hz windows, 3–8 ÿA/cm2. It follows that in such experiments one can expect the EP efficiency window in the 10–100 Hz range, 0.5–50 ÿA/cm2.

The expected frequency window of EP efficiency of 10–100 Hz coincides for both groups of experiments. With regard to the amplitude windows,

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We note the following. In the first group of experiments, the average EP within of the medium is approximately two orders of magnitude smaller than the external one due to the dielectric polarization of water with ÿ ÿ 80. The effective dielectric constant of the medium with cells can, as Chu [342] showed, increase several times more due to the special properties of the ions of the double electric layer surrounding the charged surface of the cell membrane. That is, the effective EP, in terms of the internal field,

fall at least in the range of about 100–1000 mV/m or even several times smaller. In the second group of experiments, the internal field can be estimated from the relation E = j/ÿ, where j is the density current in the medium, ÿ is the electrical conductivity of the medium. For biological tissues, the conductivity is of the order of 1 (Ohm m)ÿ1. Consequently, the range of effective fields corresponds to the interval 5–500 mV/m.

There are also earlier data on the sensitivity of fish to very weak EP in the range of 50–500 Hz 0.1–1 mV/m, Lissman and Machin [533]. Berg, in a compact review [282], analyzed various electrical and magnetic conditions in relation to biological processes DNA-RNA synthesis, enzymatic activity, calcium transport and cell proliferation. Optimal conditions of electromagnetic stimulation fell predominantly in the low-frequency window range at EP amplitudes of about 10–100 mV/m.

Thus, the amplitude windows for are approximately the same. two groups of experiments. In any case, there is no reason to assert that the physical mechanisms responsible for the biological effects differ in the different groups. The above estimate of the internal EP, ÿ 1 mV/m, required for ionic interference caused by the electronic polarization of ligands, does not contradict the experimental data. It is possible that the ionic interference mechanism underlies the observed windows of biological effectiveness of EP. At the same time, a larger volume is needed for a reliable conclusion

experimental material with detailed dependencies on EMF parameters.

Goldman and Pollack [450] investigated the proliferation of human fibroblast cells embedded in a collagen matrix when an alternating current was passed through the medium. The results, including frequency and amplitude dependences for two measured quantities, the rate of DNA synthesis and the rate of incorporation of tritium-labeled thymidine,

were analyzed in the work of the author and Goldman [304]. The experimental data were normalized to their control values and

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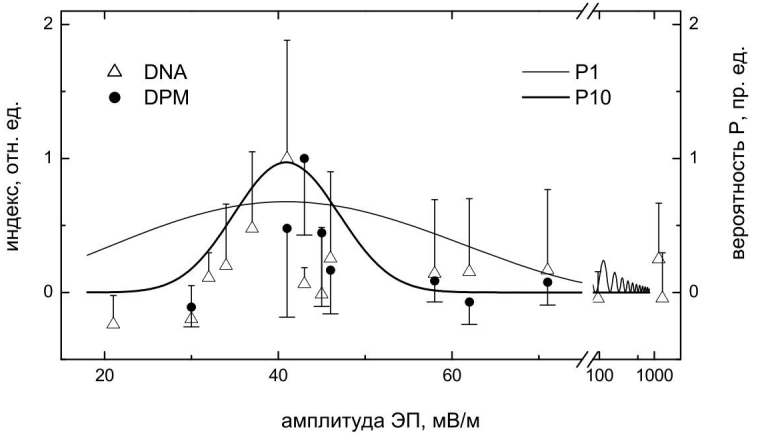


Fig. 4.49: Amplitude dependences for human skin fibroblasts in 10 Hz EP based on measurements of DNA synthesis, 3H-thymidine incorporation. P1 is the dependence of the probability of ion-protein dissociation monomer from the amplitude of the EP (4.110), Eÿ ÿ 40 mV/m; P10 is the same for an enzyme activated by ten monomers.

renormalized to a unit maximum value. They are shown in Fig. 4.49 and Fig. 4.50.

The data were compared with the theoretical conclusions presented in section 4.6. As already noted, the positions of the frequency peaks interference in the alternating gradient EP corresponds to the main Larmor and cyclotron frequencies. Static and relatively slowly changing gradients due to proximity ionic system to other related charges such as atomic groups with dipole moment shifts spectral peaks to new positions depending on the magnitude of these gradients. This means the need to average the theoretical probabilities of dissociation over the possible values of the static gradients of the EP. Such averaging leads to the broadening of frequency peaks. Therefore, the relatively wide maximum of the frequency dependences in Fig. 4.50 is explained by the wide distribution of quasi-stationary endogenous EP gradients near the ionic targets excited by exogenous variable gradients.

On the contrary, the experimental dependence on the amplitude is already the theoretical dependence P1, Fig. 4.49. In the work [304] the author and Goldman noted that the biochemical interpretation of this may be related

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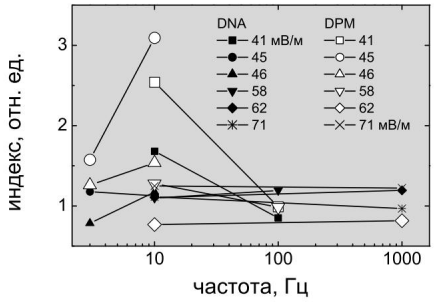


Fig. 4.50: Frequency dependences for fibroblasts in EPs of different amplitudes. The points obtained connected at the same amplitude straight.

with the presence of enzymes that include several identical subunits, ion-protein monomers, each of which dissociates independently of the others. Let the enzyme activation require the same state of all monomers over a characteristic time interval

conformational transition of the enzyme into the active state. Obviously, the probability of activation of an enzyme with two monomers is proportional to the square of the probability of dissociation of the monomer, with three monomers, — cube. This leads to a narrowing of the efficiency windows of the field parameters and to the fact that the chances of an enzyme with n monomers being active will be significantly less. However, if the concentration of enzyme molecules is large enough, then there will be a biologically significant amount of active molecules. This idea is illustrated in Fig. 4.49 by the curve P10. It represents the result of raising the original curve for the monomer to the tenth power and scaling accordingly.

■ Note that this mechanism is a "biochemical amplifier" of the external signal. Let, for example, the probability (in units of time) natural dissociation of the monomer in the absence of constructive interference caused by special combinations of frequencies and amplitudes excitation, there is P, and it increases only slightly when the excitation parameters fall within the efficiency window: P + P. The signal-to-noise ratio that could be associated with this case is P/P.
The probability of natural activation of an enzyme with n monomers is W = P n, since activation due to various random factors, including noisy electric fields and gradients, occurs independently for each of the monomers. In the efficiency window

it is equal to W + w =(P + P)n. In this case, the signal-to-noise ratio w/W is equal, as can be easily calculated in the PP approximation,

$$w/W \ddot{y} nP/P ,$$

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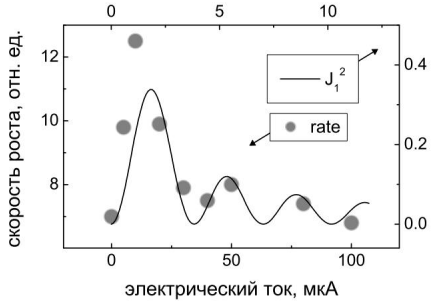


Fig. 4.51: Dependence of cell growth rate on the value of direct current in the environment, according to data [285].

that is, n times better. This increase is even more significant, ÿ 2n, if the probability P is comparable to the natural level of P. Recall that these the quantities depend on the initial conditions of the ion in the binding cavity. With the initial excitation of states with only small values of the magnetic quantum number, and only they can be excited by thermal perturbations of the ion in the binding cavity, the magneto-dependent part of the dissociation probability is just comparable with the constant level.

Bechkov and Peeva [285] discovered a polyextreme dependence proliferation of *Acetobacter suboxydans* cells when passing a constant electric current through the cell medium in the range 0–100 ÿA. Although the theoretical dependence of the dissociation probability ion-protein complexes from a constant electric field by us was not considered in detail, a comment on this experiment with from the point of view of ionic interference is possible. It takes into account the rotational states of many potential biophysical structures - targets of the electric field. From the point of view of rotating For ion-protein complexes, the applied constant electric field is variable and, accordingly, causes variable EP gradients. Therefore, for rotating complexes, the dependence of the effect on the magnitude of the external constant field should be similar to

dependence on the amplitude of the alternating field for relatively stationary complexes. The latter, as has been shown many times above, has the motif of the square of the first-order Bessel function. On Fig. 4.51 shows the experimental data with the diagram superimposed on them. function J2 1. In contrast to exposure to variable MP, theoretical the value on the abscissa axis, which has the meaning of the amplitude of the variable gradients of the EP, is not a measurable value in the experiment. Therefore, it is necessary to perform scaling on both axes for the sake of compatibility.

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displacement of theory and experiment. This reduces the value of the conclusions following from the correspondence. However, in any case, the similarity itself forms of experimental and theoretical dependence are unlikely to be random. on.

4.10 Heuristic probability assessment MBE involving ions

Most biochemical transformations in the body occur in the presence of enzymes - biological catalysts. Usually in The enzyme has an active center containing a catalytically active non-protein group called a cofactor. Cofactors are composed of Many enzymes contain ions of various metals, as well as vitamins and their derivatives. The main reasons for the high activity and specificity of enzymes are to ensure the correct orientation of the reacting groups of the enzyme and substrate, competition between several catalytic groups of the active center of the enzyme, and a strong difference in the dielectric properties of the medium in the region of the active center from the corresponding values in the solution. These factors ensure the acceleration of the catalytic biochemical reaction by up to 108–1012 times.

More than 3,000 enzymes are known. About a third of them contain complexing transition metal ions as cofactors. Many enzymes also have a special site where

interaction with substances that control the catalytic activity of the enzyme. Such substances can also be metal ions and complex ions. In addition, metal ions are included in the composition of non-enzymatic proteins that perform important vital functions. Thus, metal ions are often key factors that trigger a particular biochemical process. Therefore, their potential involvement in MBE as targets is highly probable.
magnetic field.

Let us give some well-known examples [59, 190, 14]. Potassium K+ and sodium Na+ ions provide a natural balanced the acid-base balance of the body, the processes of transmitting excitation signals along nerve cells. These ions are the working fluid proteins - ion pumps, for example (Na,K)-ATPase. Pumps create a difference in electrical potential on the cell membrane due to increase in the concentration of potassium in the cell and sodium in the extracellular environment de.

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Magnesium is a biological activator of a group of enzymes, kinases that transfer phosphate groups from ATP molecules to various substrates. Magnesium ions Mg2+ are coordinately bound to Porphyrin ligands form the basis of the chlorophyll molecule, which participates in photosynthesis in plants, algae, and some bacteria.

Calcium plays an important role in the body's functioning. Calcium ions Ca2+, by binding to certain proteins, calmodulin, troponin-C, etc., These proteins control the activity of many enzymes. Calcium ions are involved in many biological processes.
This, in addition to enzymatic activation, synaptic transmission, secretion, flagellar motility, processes of muscle contraction, reproduction, growth and development.

Many enzymes contain zinc ions Zn2+: carbonic anhydrase, which decomposes carbon dioxide, carboxypeptidase A, which hydrolyzes proteins, alcohol dehydrogenase, some polymerases involved in protein synthesis, phosphatases, etc. Zinc ions and manganese and copper ions with similar properties stimulate the transport of nutrients, oligopeptides, by modulating their affinity for binding

membrane transporter sites, which may have physiological significance [364]. A connection has been established between cancer and the amount of zinc in the body, and its connection with the functioning of the endocrine glands and the insulin system.

Manganese ions Mn2+ are in many ways analogous to magnesium ions in the metabolic process. Manganese is essential for the functioning of enzymes, involved in phosphorylation processes. It is a component of pyruvate carboxylase and arginase, and stimulates the synthesis of vitamin C, cholesterol, and some fatty acids.

Molybdenum is essential for many biochemical reactions. It is a coenzyme in the active center of nitrogenase, catalyzing processes involving nitrogen. The enzymes aldehyde oxidase and xanthine oxidase, which are involved in purine metabolism, also contain molybdenum. An imbalance of molybdenum in the body causes a number of serious diseases. Plants contain molybdenum in nitrate reductase, which is important for nitrogen metabolism.

Iron is part of the porphyrin group, forming heme, with the ion Fe2+, or hemin, with Fe3+. In this form, iron is present in hemoglobin, myoglobin, and cytochromes, which ensure oxygen transport in the body. Heme is contained in the enzymes catalase and peroxidase, which regulate the level of hydrogen peroxide in the blood. From one to several dozen Fe3+ iron ions, which interfere with replication, have a molecule

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la DNA. Transferrin is a protein that transports iron in the body.
me.

Several dozen proteins and enzymes are known to contain copper: albumin, ceruloplasmin (Cu+ and Cu2+ ions), cytochrome oxidase, albo-, cerebro- and neurocupreins, tyrosinase, lysyl oxidase. In plants, copper is involved in the formation of chlorophyll. Ion cobalt Co3+ in the corrin group, similar to the porphyrin group group, contains vitamin B12 (cobalamin). In addition, cobalt is an activator of the enzymes carbonic anhydrase and carboxypeptidase (Co2+). Chromium and nickel play a relatively small role in biochemical processes. However, the deficiency of chromium ions causes a number of diseases. Nickel activates trypsin, arginase, and carboxylase and other enzymes.

It is believed that cesium Cs and strontium Sr are essential for the body, However, their physiological and biological role is not fully understood. Rubidium ions Rb+ are used in experiments to replace ions potassium and the study of biochemical processes involving it. Lithium ions Li+ have been considered in the literature as possible targets of MP in in the body of mammals. The trace elements also include the metallic elements vanadium and tin.

The content of inorganic ions in organisms is quite high, in On average, there is one ion per several hundred water molecules. The distance between adjacent ions in such a "broth" does not exceed ten to twenty A ^{o}. The role of various ions in the mechanisms of magnetobiological reception is only beginning to be studied. Therefore, a priori *heuristic* analysis of the probable contribution of ions to is useful MBE.

Ions that are part of living tissue, blood, cytoplasm, etc., are not equivalent in terms of their ability to enter into various biochemical reactions. Some ions react more easily with other molecules. The rate of their circulation in the system of metabolic processes is higher. It would be natural to link the effects of weak magnetic fields with precisely these ions. The ability of chemical elements to undergo reversible reactions is generally associated with their ionization potential, that is, the energy required to remove valence electrons. This value strongly correlates with the relative electronegativity of elements, their ability to attract electrons valence bond cloud. The most "mobile" are alkaline and alkaline earth metals. Then comes the group of transition metals. Figure 4.52 shows data for the most important, in biological

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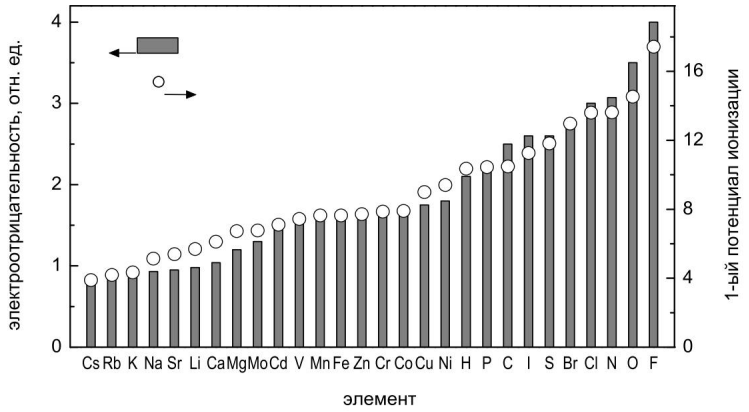


Fig. 4.52: Electronegativity and first ionization potential
some biologically significant elements.

plan, elements.

It has been noted in the literature that harmonics and subharmonics of cyclotron frequencies of different ions are often very close to each other, which makes it difficult separation of their possible contributions to the MBE. It is therefore natural to form an integrated representation of the frequency spectrum at which, theoretically, the maximum MBE is possible.

The following remark is important. Apparently, free ions in solution are not targets of magnetic fields. In this state, the ion has coordinates and momentum, which change extremely in a weak magnetic field. insignificant. Therefore, in particular, halogen ions in solution, as well as in the composition of strong covalent molecular bonds, are not taken into account below. The elements Al, B, C, Si, N, P, O, S, which also form relatively strong covalent bonds.

Of more interest are the bound ions that act as a complexing agent in the complex compound, the central cation surrounded by ligands. The coordination bond of the cation with ligands is of a significantly different nature for alkaline or alkaline earth metals and for transition metals. With the former, Due to their low electronegativity, the ligands form almost ionic bonds. The electron clouds of the bonds are pulled toward the ligands, where usually there are elements with high relative electronegativity, O, N, etc. In this case, the electric charge of the central

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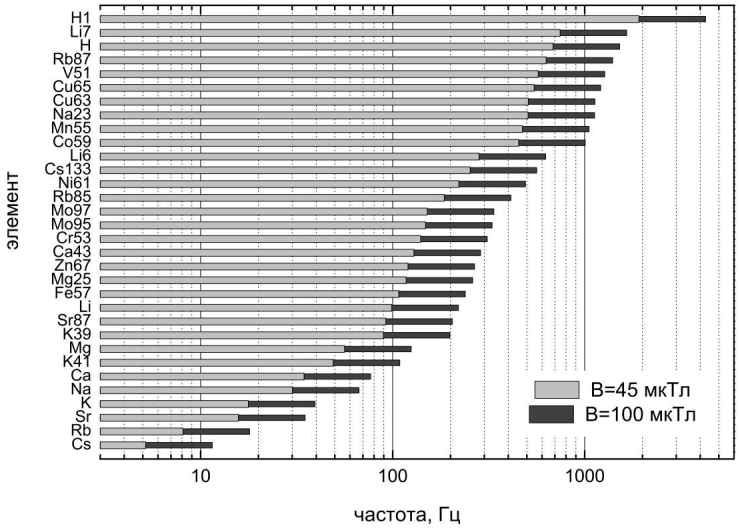


Fig. 4.53: Cyclotron and NMR frequencies of ions and isotopes of vital important elements. Isotopes with indicated mass numbers correspond to NMR frequencies.

ion (in electron charges) corresponds to or is almost equal to its valence.

The situation is different with the ions of transition elements, whose electronegativity is greater than that of alkali and alkaline earth metals.
Now the electron clouds are not too strongly biased towards the ligands,
The bond is nearly covalent, and the charge of the central ion is shielded by covalent electrons. Thus, the 2+ in the designation of the Fe2+ ion in heme does not correspond at all to its electric charge. For this reason, determining cyclotron frequencies for nearly covalently bonded transition metal ions is difficult.

Hydrogen is involved in both covalent and hydrogen bonds, which are the majority in the living environment, which consists of 90–95% water.
Due to the specific properties of hydrogen bonds, hydrogen atoms form H+, OH+ ions

3 and others with a well-defined charge.

Thus, considering the spectrum of the cyclotron frequency series,
we will limit ourselves to ions of alkali and alkaline earth metals, hydrogen, and also magnesium, which occupies an intermediate position

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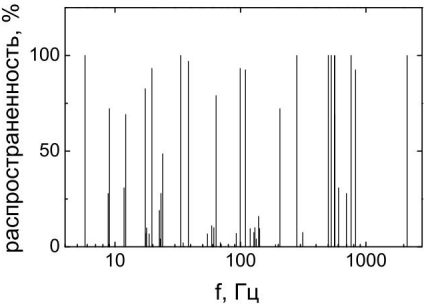


Fig. 4.54: Cyclotron spectrum and NMR frequencies and distributions the corresponding elements comrade

in the electronegativity series:

$$Li+, Na+, K+, Rb+, Cs+; Ca2+, Sr2+;H+; Mg2+ .$$

For the NMR frequency spectrum of the series we present those isotopes of elements essential for life that have a nuclear spin and are naturally distributed whose strangeness is more than 1% and 43Ca, due to the potential importance of calcium. This list includes

1H, 6.7Li, 23Na, 25Mg, 39.41K, 43Ca, 51V, 53Cr, 55Mn,
57Fe, 59Co, 61Ni, 63.65Cu, 67Zn, 85.87Rb, 87Sr, 95.97Mo, 133Cs

see also Table 6.1. The cyclotron and NMR frequencies of the indicated elements in the MF BDC = 50 ÿT are shown in Fig. 4.53.

It is evident that cyclotron frequencies are primarily concentrated in the 10–100 Hz range, while NMR frequencies are in the 100–1000 Hz range. The uneven distribution of these frequency ranges is also noticeable.

Fig. 4.53 is not complete. The effective electric charges for transition metal ions, as mentioned above, are unknown, so a series values of fc are absent from the figure. Since the abundances of the indicated isotopes of the elements vary, the interference frequencies corresponding to them acquire “weight”. In Fig. 4.54, the abundance of a given isotope is shown for each of the interference frequencies. It is evident that on the frequency axis there are sections with a large total "weight" of the spectral lines included in them.

The cyclotron and NMR frequencies are defined here not because these physical mechanisms are involved in MBE, but because the response of bound ions occurs at these frequencies, their harmonics and subharmonics. If we take into account the interference mechanism of MBE, then several satellites can be added to the above frequency series, determined by the formula of the ion interference spectrum. Obviously,

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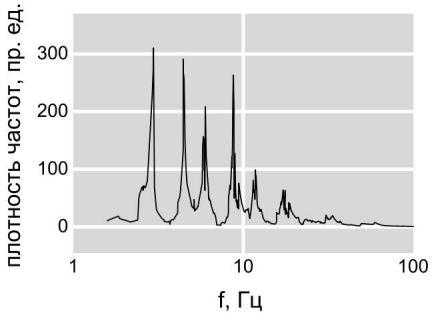


Fig. 4.55: Interference density cyclotron series frequencies, m = ÿ2, .., 2, n = 1, .., 4 in magnetic field BDC = 50 ÿT.

In this case, a fairly dense series of interference frequencies arises. Let us restrict ourselves to the spectrum of the cyclotron series, fmax = mfc/2n. Let us estimate its density, taking into account that the relative “weights” of the satellites at a priori equality of all elements of the matrix a{i} is approximately equal to we

$$\frac{1}{m} J2\ n(n1.8)\ ,$$

at the optimal ratio HAC/HDC ÿ 1.8. We will estimate the density as the ratio of the sum of the weights of the interference frequencies falling within a small spectral interval to the width of this interval. Constructed thus smoothed spectrum of interference frequencies, taking into account natural abundance of elements is shown in Fig. 4.55.

Naturally, complex ions fall out of this analysis, which Also, ions of a number of transition metals with a previously unknown charge can play an important role in the MBE.

The curve in Fig. 4.55 is rather arbitrary. At best, if we consider the sign and magnitude of the MBE in a randomly selected biological system to be random variables, then with some caution the curve, more precisely, the square root of this function could be interpreted as *a heuristic* estimate of the probability density of detecting MBE by the mechanism of ionic interference under appropriate magnetic conditions l.

4.11 Limits of applicability of the ion interference mechanism

Experiments show that genetically different types of cells of the same functional orientation in general react differently to the same MP. Cancer cells of different types were studied in

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[398] For the two types of E. coli cells, no differences were observed.
not only in magnitude, but also in the position of the peaks of the frequency spectrum of the MBE
[635] The results of experiments on the effect of MF on the mobility of diatoms also
depend on the biological line of these organisms
[334] Peak frequencies may also depend on the state of the cell population.
Thus, *E. coli* cells of the stationary and logarithmic phases of population development
showed MBE of the opposite sign, and the peak shifted
by frequency by 3–4% [246].

The bound ion interference model does not explain these differences in number. It
can be assumed that this is due to different
target ions in cells, or even different combinations of ions
[125]. This assumption obviously takes the question out of the scope of discussion
from the point of view of physics. Why are the ions responsible for the MBE in
In some cells, one function, and in other cells, the same function is different - this is a
question from the field of biology.

Within the framework of the ion interference model, a significant factor is
for the shape of the spectra is the distribution of the populations of the states
with different values of the magnetic quantum number at the initial moment of time
when the ion enters a metastable state inside
molecular capsule. It is clear in advance that the initial conditions must
depend on many factors, primarily on the conformational state of the molecule. It
determines the physical characteristics of the "gate." Therefore, conditions such as
temperature, pressure,
concentrations of substances on which the conformation of molecules itself depends,
are also capable of changing the shape of the MBE spectra. It should be noted that
the dependence of MBE on temperature was observed in [370, 315], concentration
The dependencies of the MBE are numerous, [229, 564, 353], etc. The importance
The biological parameters for observing MBE are indicated in [568]. Such dependencies
also fall outside the scope of the interference model, which explains them only
qualitatively.

The model is currently unable to explain why sometimes very small amplitudes of
an alternating magnetic field are effective against the background of a moderate
parallel constant field. Estimate
frequency-amplitude boundaries is shown in Fig. 5.18. Basic model
gives the maximum effect for fields, alternating and direct, of the same order of
magnitude. In [250, 397, 626, 405] and others, MBE was observed
in an alternating magnetic field of the order of 0.1 ÿT, which is five hundred times less than the level
GMF. In [369, 390], the biological effects of low-frequency pulsed fields at ÿfh < 0.05
ÿT were studied. It is likely that the
other mechanisms. In the works [144, 142, 143] the effect arose when

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relative amplitude of the magnetic field of the order of 10ÿ3 and did not occur at 10ÿ1. This may be due to the presence of an electric field and current in the electrochemical cell used in these studies. Let us recall that
The interference mechanism for rotating complexes predicts sensitivity to ultra-weak magnetic fields. However, this required
the presence of quantum states with lifetimes greater than 10 s at physiological temperatures. *A priori* this seems unlikely, although constructions such as a molecular gyroscope (see Chapter 5) could provide such lifetimes for the gyroscopic degree of freedom.

There are many experiments in which the agreement between calculated and experimental data is quite satisfactory. This indicates that
behind the speculative processes of the theory there are real physical processes of interference, which could underlie some
magnetobiological effects. The interference nature of the action of magnetic fields on the angular modes of the quantum states of ions and molecules, when only their phases change, leads to the fact that the energy required for a noticeable bioeffect is quite small. It can be calculated in
in terms of ÿ ÿ.

Today, the mechanism of ion interference describes polyextreme effects a) modulated in magnitude and direction
MF, b) magnetic vacuum, c) constant MF taking into account the proper quantized and classical regular rotations of ion-protein
complexes, d) pulsed MP against the background of parallel constant
MP, e) modulated by the magnitude of the MP in the NMR frequency range, f) in low-frequency electric fields, g) in amplitude-modulated
microwave field, h) interference of states of rotating molecular groups, i) shift of spectral peaks of dissociation probability during rotation of biological samples, j) magnetic noise. The predictions of the theory of ionic interference (see Index) are formulated in such a way that they can be tested experimentally.

At the same time, the theory of ion interference is, in a certain sense, phenomenological. Apparently, it should be identified for the time being as a semi-phenomenological model.
On the one hand, this theory deals with the microscopic dynamics of particles, but on the other hand, it is built on the postulate of a large
lifetime of angular modes and does not consider physical processes, ensuring the preservation of the projection of angular momentum on the direction of the magnetic field.

The metastability of angular modes could be explained by details interaction of the ion with the walls of the cavity. For reasons of electrical

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statics the position of the ion in the center of the cavity is not stable.
shifts and binds more to one of the ligands. The process of ion displacement and the response adjustment of ligands has the same time scales as the vibrational dynamics of the ion. Therefore, the idealized equation of ion dynamics must take into account the self-action of the ion. Where the probability density of the ion is higher, its potential

begins to decrease due to the adjustment of the ligands. In the dynamic equation, this corresponds to an additional term of the Hamiltonian, proportional to the square of the modulus of the wave function, which describes
self-action. The wave function seems to deepen a potential well for itself, and most of all where its density is high. The resulting
the equation, accurate to the energy of interaction with the magnetic field, is the nonlinear Schrödinger equation (NLS), for which in one-dimensional
In this case, the soliton solution is known.

The soliton states of the ion in the protein cavity explain the stability of the dynamics under thermal perturbations. The effect of thermal perturbations could be represented as an additional additive random factor depending on time and coordinate.

at a certain threshold amplitude of the random potential, the soliton-like excitation decays relatively quickly. However, it is known [73, 99, 692, 736] that with a further increase in the amplitude of the disturbances
Long-lived soliton-like excitations may arise again.

If the binding ligands are located at the ra sites, then the following NLS equation is suitable for the states of the ion in the MP, which
takes into account both magnetic and thermal factors:

$$i\,\frac{\partial}{\partial t}\psi(r,t) = \frac{P^2}{2M} - \frac{q}{2McLH} + \sum_a U_a\,\delta(r - r_a(t))\,|\psi|^2\psi.$$

Here L = ir ×ÿ is, as before, the angular momentum operator, Ua
— potential of the ion in the field of the a-th ligand, ÿ, f(r) are the parameters of the model. The fluctuating coordinate of the a-th ligand ra(t) corresponds to thermal
vibrations of the medium. The numerical solution of such equations is sometimes realized in the form of soliton-like disturbances, stable in a certain range of parameters of thermalizing factors.

The theory of interference of bound ions will probably turn out to be only
a small step in the right direction. Future, more advanced models will answer the question of why the idealization of long-lived
angular states is in such good agreement with experiment. One such model—the interference of a molecular gyroscope [305]—is described in the next chapter.

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Chapter 5

Prospects of electrical and magnetobiology

5.1 Possible role of water in magnetoreception tions

It has been established that in relation to finely organized biological processes, water turns out to be not only a passive medium for the flow of these processes, but also an active participant in them. Water retains information about the history of physical impacts, which significantly affects the processes occurring in the aquatic environment. This circumstance, along with with the very fact of long-term memory of water, it represents a certain prospect for the development of new channels for controlling chemical, biochemical and biological processes.

Biological activity of water is a property of water determine, within certain limits, the parameters of the vital activity of biological objects placed in it or associated with it. Being provided itself, water under normal conditions (room temperature, atmospheric pressure, the presence of gas exchange with the environment, electromagnetic background of natural origin, etc.) over time from a day to several months comes to a quasi-equilibrium state, a state which, on average, does not change further. The average state over a sufficiently large time interval, obtained on the site

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quasi-equilibrium, we will call the equilibrium state. The current deviation of the state of water from equilibrium is caused by fluctuations or regular deviations of the physical agents acting on water from the values corresponding to normal conditions. Equilibrium water does not possess biological activity by definition and serves as a natural control environment. It is clear that various physicochemical properties of water come to equilibrium with different

speed.

Physical influences that cause specific biological activity of water include magnetic treatment of water, obtaining melt water, degassing, etc. Depending on the situation, the nature of the biological activity of water is associated, for example, with very little

content of dissolved gases after degassing, while maintaining
in water ice-like microclusters after thawing, etc. In all
In some cases, the biological activity of water arises as a result of water being in metastable (different from equilibrium) states, regardless of the nature of these states.

Water has long attracted the attention of researchers as a possible
a universal mediator in the transmission of electromagnetic field signals to the biological level. The biological action of EMF is associated in this case with altered states of water [107, 76, 109, 18,
20, 549, 255, 617, 115, 147, 103, 451]. The change of state occurs
due to the impact of external fields on water and is transmitted further to
biological level due to the participation of water in various metabolic reactions. It is interesting to know whether water can change under the influence of
weak fields, remember the magnetic history, and what is then in the water
could be a target of EMF action.

In the author's work [20], the nuclear spins of water protons were considered as primary targets for the magnetic field (MF). They interact with the external MF by their magnetic moments and simultaneously participate in spin-orbit interactions with the states

spatial degrees of freedom. The hypothesis was that special quantum states of protons are metastable and capable of influencing the rate of formation and dissociation of structural associates in water
[19], biochemical processes. However, the method for testing this statement was not discussed.

5.1.1 Experimental evidence for water memory

There are many experiments that indicate that liquid
Water has a memory for various physical and chemical influences.

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One of the physical influences that leads to the emergence of biological activity in water is the procedure of multiple dilution of a solution of any preparation, used, for example, in homeopathy. Successive dilution of the initial solution reduces the concentration of the substance (effector) molecules until

there are no molecules left in the working solution. However, even in this case, it is equal As with further dilutions, water retains specific biological activity in a number of experiments. This allows us to speak of liquid aqueous media obtained in this way as imaginary solutions; the term was introduced in [18]. The literature also uses

the term "super-dilute solutions" reflects not the essence, but the preparation procedure, and therefore leaves room for debate
about the presence of effector molecules in the final preparation.

One of the first scientific observations of biological activity
imaginary solutions using a specific biotest refers to the end
last century. Experiments were conducted with imaginary solutions of homeopathic preparations of aconite, thuja, gold, and table salt. The solutions were prepared in a pharmacy using standard homeopathic procedures,
introduced into medical practice by S. Hahnemann about two hundred years ago. The biotest measured a person's reaction time to a visual stimulus. The reaction was trained to become automatic.
In this case, the reaction time became independent of the operator's will and objectively reflected his internal state. The operators were allowed to smell the imaginary solution. Here is how the famous Russian organic chemist A.M. Butlerov described these experiments in 1882 [34]:

> According to Jaeger's experiments, not only did it turn out that homeopathic remedies act definitely even in the higher (in hundredths and thousandths) liquefactions, but it was also confirmed the generally accepted opinion among homeopaths is that the action is enhanced through liquefaction. (...) Aconite in the initial tincture reduced excitability, and in liquefactions in general increased it, and the maximum effect was found at 15-liquefaction. In further liquefactions, activity
> aconite decreases to some extent, but then again, at 150 liquefaction, the dose maximum, but not as high as the first. begins to increase and reaches a new
> (...) The characteristic features of the action turned out to be the same
>
> the same in aconite of 100th dilution, taken from different pharmacies. It is remarkable that for thuja, salt and gold there was also an increase in activity up to the 15th dilution. This

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the fact was stated equally by different observers. But
Even more remarkable is the amazing result that ordinary (table) salt
exhibits the main maximum
action in two thousandth liquefaction, although the first maximum for
it, like for other means, occurs at the 15th liquefaction.
marriage.

Over the past decades, interest in the problem of biological
the activity of imaginary solutions has steadily increased. A review of the work of this
directions, works that clearly demonstrate the existence of memory
water, can be found in Burlakova's article [33] and in the author's work [18].

Research into water and water systems is traditional in
many fields of science; the physical and chemical properties of water, the history of
research are described, for example, in the monographs of Frank [711],
Eisenberg and Kautzman [221], Antonchenko, Davydov and Ilyin [9].
The role of water in biological systems and processes has been discussed, for example,
Privalov [165], Watterson [193], Aksenov [5]. Here we will limit ourselves to works
in which the memory or metastability of water is manifested in connection with
electromagnetic processes. Below are just a few
recent works on this topic.

Berezhinsky, Gridina et al. [39] showed that microwave radiation with a
frequency of 51.5 GHz and a power of several mW/cm2 for five minutes changed
the optical refractive index of liquid water by
$n = 2.5 \times 10^{-4}$. This is an order of magnitude greater than the change in the
refractive index due to equivalent heating of a water sample. The effect was
frequency selective. Measurements were carried out on a He-Ne laser interferometer.
Obviously, the change in structural rearrangements
in water, detected by the polarizability of electrons, relaxes with a characteristic time of at
least 5 minutes.

Singh, Rai et al. [255] report that water remembers the effects of microwave
EM radiation. Treated with such
EMF water caused changes in the development of blue-green algae,
cyanobacteria.

Fesenko, Geletyuk et al. [617] showed that an aqueous solution used in
measurements of the activity of calcium-dependent potassium channels remembers
the effect of microwave radiation. The activity of the channels was measured using
the patch-clamp method, in which a microscopic section of the membrane with
channels covers the tip of a micropipette immersed in the solution and turns out to
be a section of an electrical circuit. Change

1See note on page 35.

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channel activity leads to a change in current in the circuit. Since the channels there are only a few in the micro-area, and each of them can be located in the open or closed state, the current change is discrete. Data processing allows us to measure the probability of an open state of a single channel. In the experiments, continuous microwave radiation at 42.25 GHz, 0.1–2 mW was applied for 20–30

min either on the solution-membrane-pipette system [376], or only on solution. In the latter case, the treated solution replaced the identical but untreated solution already present in the system, and through We observed changes in channel activity for several minutes. Changes were the same as in the case of direct exposure to the system.2 The changed state of the solution remained after 20 minutes. The authors concluded that the effect of microwaves on the state of ion channels is due, at least in part, to a change in the properties of the solution. It is suggested that such a change could be associated with gas exchange. on the surface of solutions, with a change in the concentration of the dissolved oxygen in water under the influence of MM.

Indeed, Kazachenko et al. [50] found that microwave radiation of this frequency at the specified irradiation time and power of the order of 5 mW/cm2 caused a decrease in the concentration of free oxygen in water and weak salt aqueous solutions by approximately 1–3%. The water transitioned to a new physical and chemical state, resistant to mechanical mixing and thermal convection. The new state was maintained for more than four hours. Water aeration by blowing I changed the concentration of molecular oxygen, but these The changes relaxed in just 10–20 minutes. A frequency response was noted. the dependence of this phenomenon, as well as the fact that it is observed only in the presence of impurities and ions. The authors conclude that microwave exposure can affect the macrostructuring of water caused by impurities.

Fesenko and Gluvshtein [436] investigated changes in water induced by microwave radiation using another physical method. They measured the characteristics of damped voltage oscillations on the plates of a capacitor filled with water, under pulsed excitation.

contour. Computer analysis of low-frequency oscillations showed the presence of two well-defined peaks in the oscillation spectrum near 5 and 47 Hz. Exposure of the cell for several minutes in a microwave field.

2Experiments showing the same effect of salt solutions treated with EM fields and solutions obtained by adding salt to water treated in this way have been known, according to data [107], since 1934.

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The new 36 GHz radiation resulted in suppression of the 47 Hz peak.
This state of water was maintained after the microwave field was turned off for tens of minutes or hours, depending on the power.
radiation power. It is remarkable that radiation with a power of 50 ÿW/cm2
had a much more pronounced impact on the system than in
A hundred times more powerful radiation. The authors discussed stable water-molecular associates that exhibit the property of remembering electromagnetic influences.

Konyukhov et al. [116, 115] report the observation of liquid water with a deviation from the equilibrium ratio of the amounts of ortho- and para-water molecules H2O (see section 2.5). Adsorption of water molecules from gas
phase, sensitive to the rotational state of water molecules, makes it possible to obtain water enriched with the ortho fraction by controlling the spin state of ortho water in a resonant magnetic field. Such spin-modified water relaxes to equilibrium in tens of minutes at
room temperature and months at liquid nitrogen temperature. The concentration of different spin fractions of water was measured by the intensity of the corresponding line of the rotational spectrum of the water molecule.
in the microwave range. The authors suggested the biological activity of spin-modified water.

Pandey, Garg et al. [389] report that water, pre-
treated with constant MF, affected the duration of the period or
the estrus cycle of female mice and weight gain during the experiment
(28 days). New water samples were placed on the surface daily.
standard permanent magnets for a period of one to eight hours,
After which the mice were given this water to drink. The presence of estrus was also determined daily by microscopic examination of a vaginal smear. The magnetic field on the surface was 0.3 T. It turned out that
that the proportion of extended cycles increased statistically significantly, $p < 0.01$, by 40–80%, depending on the exposure time. The increment
the weight of mice that were given treated water amounted to 10–20%,
while in the control this value was no more than two percent.
Rai, Garg, and Vashita [623] found that water treated in a similar manner changed the photosynthetic activity in unicellular green algae several-fold. In these studies, gas exchange between samples
liquids and the environment were not controlled.

Lobyshev, Ryzhikov and Shikhlinskaya discovered that distilled water exhibits weak luminescence in the near ultraviolet and visible regions of the spectrum [127]. The emission spectra excited by ultraviolet light contain relatively broad lines with a length of

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waves of 360 and 410 nm. The intensity of luminescence depended on the storage time of water, the preparation conditions, the presence of a controlled impurities, electromagnetic and heat treatment [536]. Spectrum of times relaxation of metastable states varied from hours to several months. Interestingly, the relaxation process was non-exponential, sometimes oscillatory. The authors emphasize that these results cannot be explained by the luminescence of impurities present in distilled water. The described luminescence is

property of water itself. It is assumed that it is associated with the presence in water there are different types of defects and molecular clusters or associates with characteristic radiation centers, the role of which can be played by dissociated protons of water.

The luminescence spectra of water were also measured by Novikov, Kuvichkin and Fesenko in [145]. They used the previously discovered resonance mode of magnetic treatment b(4 10ÿ2)B(42)f(3.7), effective with respect to a number of amino acid solutions. The luminescence of a solution of bovine serum albumin and other proteins, as well as the luminescence of water, were measured. In the latter case, after 2–4 hours of treatment, the intensity of both the short-wave and long-wave luminescence bands increased severalfold. The admixture of treated water had a specific effect on the protein,

similar to what happened with direct treatment of the protein solution with a magnetic field. The presence of effects of multi-hour memory of water is obvious. The authors of the study explained the effect in terms of macroscopic water clusters, possibly possessing biological activity.

Devyatkov, Kislov et al. in [147] and Katin in [103] showed that that human ingestion of water pre-treated with microwave radiation from a standard medical device entails is a natural change in the physiological state of a person compared to the condition after the control intake of untreated water. In both cases, the human condition was measured using the potentials of biologically active points. In [103], the water exposure lasted for 15 minutes, and the altered state was maintained for 4–6 hours.

Khizhnyak and Ziskin [509] observed the emergence of convective vortices in liquid water when irradiated with mm waves with a frequency of ÿ 49 GHz, starting from very low power levels of 1 nW/cm2. After 20–40 min After the start of the irradiation, the vortices disappeared and they were launched again in the same conditions failed within ÿ 4 hours. According to the authors, this was caused by the induction of a state of water with altered viscosity, perhaps

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be due to gas exchange.

Interesting experiments demonstrating the presence of water memory in response to electromagnetic influences were conducted by Burden, German and Skarzha [280]. Electrophotography was used to study the characteristics of a corona discharge (Kirlian effect) occurring near the surface of water droplets deposited on photographic paper in a high-voltage, 12.5 kV, high-frequency, 45 kHz field. Photographs of simultaneous discharges from two droplets were processed on a computer, taking into account eight parameters of the emerging discharge pattern. Thus, the difference in the states of two identical

drops of water. The drops differed only in the details of the preparation of the image. ts of water.

Initially, identical water samples were taken in identical glass containers. vessels. Quartz test tubes containing germinating spruce seeds, living or dying, as well as flour beetle larvae and pupae, were immersed in them for several hours. This way, chemically identical water samples were obtained, which

could differ from each other only by changes induced ultra-weak radiation of organisms. For each pair of compared From 20 to 45 repeated measurements were carried out on the samples. It turned out that photographs of discharges from drops of these samples are statistically significant differ from each other. The authors suggested that the differences reflect metastable changes in the structure of water caused by ultra-weak electromagnetic radiation from organisms. Previously, German, Berden, and Ruzik [492] showed that similar changes in water have biological activity in relation to the rate of germination of seeds Myan ate.

Belov, Konyukhov and Stepanov [13] showed that the level of fluctuations the dielectric constant of water increases under mechanical disturbances such as mixing and overflow. Fluctuations were studied in a volume of water of the order of mm3 between the capacitor plates. with insulated electrodes. The measuring generator was operated on frequency of 160 MHz. Frequency fluctuations associated with permittivity fluctuations were recorded with relative accuracy ÿ 10ÿ7 and converted into spectra. It turned out that the modified fluctuation spectra, of the type 1/f ÿ ÿ, ÿ = 1.3–2.0, relaxed to the original state for more than an hour. One hypothesis linked the metastable fluctuation spectra with changes in the structure of hydrogen connections.

In the work [412] Shirahata et al. showed that the so-called restored

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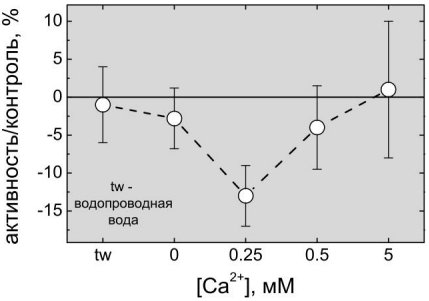


Fig. 5.1: Change in biological activity of an aqueous solution after magnetic treatment at different ion concentrations calcium, according to [643].

(reduced) water taken near the cathode of the electrolyzer, as opposed to water from the anode region, characterized by high pH values, low dissolved oxygen content, a high content of dissolved molecular hydrogen, and a large negative redox potential. In biochemical tests, this water exhibited activity specific to the enzyme superoxide dismutase. The water retained its activity for a month and did not lose it even after

such procedures as freezing/thawing, degassing, intensive shaking, boiling, filtering and autoclaving in a closed vessel. Autoclaving in an open vessel or in a closed vessel in the presence of an atomic hydrogen scavenger resulted in a loss of activity. It was hypothesized that the free radical scavenging activity of reduced water is associated with a consistently high atomic hydrogen content.

Ruzik and German [643] compared the direct effect of low-frequency MF and the effect of water/aqueous solution samples pre-treated in such a field on the germination of Canadian grass seeds. *Picea abies* spruce . The magnetic field had the following configuration

b(105 ± 7)B(22 ± 3)Bp(40 ± 5)f(50)bstray,50Hz(< 0.2)t(12 h) .

The water was treated for one day before the experiment. Then the seeds were soaked in this water and the number of germinated seeds was counted on day 5. Control samples were soaked in unexposed water. An alternative experiment involved exposing the seeds to in this MP after soaking in untreated water for 12 hours per day, with simultaneous control in the second, completely identical camera in the absence of variable MP.

Experiments revealed the biological effectiveness of treated water, which produced an effect similar to that of direct

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irradiation. In both variants, growth inhibition was observed
7–13% on the fifth day, with no effect at the final stage of germination on the seventh day.

Five experiments were conducted with different water samples for soaking/ treatment. Tap water and deionized distilled water with the addition of different amounts of calcium chloride were used,
dissociating into Clÿ and Ca2+ ions . The relative average values, Fig. 5.1, show that the biological activity of the samples
The concentration of calcium ions in water exposed to MP depends on the concentration of calcium ions.
Interestingly, similar concentrations of added calcium ions
maximized another biological effect, the mobility of diatoms in MP, see Fig. 2.8.

These experiments show that the effect of MP on biological
system may be indirect, through a change in the state of water with the participation of calcium ions. This hypothesis was first formulated
Kislovsky [107, 108] and found confirmation in the experiments of Ayrapetyan, Grigoryan et al. [549].

Akimov, Binghi, and Lazareva [3] measured the germination parameters of tomato seeds soaked in various specially treated samples of distilled water. It was found that placing water samples in steel containers in front of a household television screen resulted in a significant change in the growth pattern.

seeds. From these data it follows, in particular, that the water remembered the effect and stored this information for several hours between
by treating water samples and soaking seeds in it.

Gulyaev, Eremin and Markov [68] observed metastable states of water arising during its electrolysis in an electrochemical cell with platinum electrodes separated by a semipermeable membrane. The direct current density was 50 A/m2 at an electric field strength of 103–105 V/m. Ten minutes after the start of

electrolysis, the hydrogen index of the catholyte fraction of the initial bidistillate reached a maximum pH value of ÿ 14, against the usual equilibrium pH value of ÿ 7. The decomposition of the metastable state
under natural conditions occurred in ÿ 800 hours. The decay of the state
in an electrochemical cell without a membrane occurred at the specified
current densities in a few minutes and accelerated with increasing current density.
ka.

Special experiments have shown that the effect is not a consequence of heating the water with electricity, nor a consequence of chemical impurities. They found, that the necessary condition for the appearance of unusual water is special

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membrane properties. One suitable membrane was a 2 mm thick ceramic membrane with low permittivity. A non-uniform distribution of space charge along the membrane was noted.

axis of the electrolyzer. A relatively narrow maximum of the field strength of ÿ 106–107 V/m was shifted from the membrane towards the cathode. The authors suggest that the metastability of water in these experiments is due to the appearance of ions $(H9O4)^+$ in the catholyte fraction, which is manifested in in the form of its strong antiviral activity.

Kalik and Morse in their work [348] showed that the memory effect of water on 15-minute 27 MHz radiofrequency exposure is closely related to the presence of dissolved gases in water. Various aqueous systems, solutions, suspensions, etc., prepared from conventional initial aqueous solutions and degassed with a vacuum pump within 30 minutes.

The electrophoretic mobility in the rutile suspension underwent periodic changes of ~100% after radiofrequency EM treatment. Solutions degassed both before and after EM treatment, They were given suspensions in which there were no changes in electrophoresis occurred. Similar results were obtained in the process of formation and precipitation of calcium carbonate precipitates, according to measurements turbidity of the suspension, as well as by the distribution of the sizes of the precipitates into the sediment of particles.

These and other experiments [348] indicated that degassing of the initial solutions eliminated the long-term effects of EM treatment. An important observation was also that A constant magnetic field caused the appearance of traces of hydrogen peroxide in the solution in quantities ranging from nanomoles to micromoles (measured by a spectrofluorometer). Analyzing their own and published data, the authors concluded that EMF also induces the appearance of small amounts of ozone, superoxide, and atomic hydrogen in water. The latter, according to the authors, is retained by water for months, and heat treatment by freezing-thawing or boiling does not remove atomic hydrogen from water. It is assumed that the effect of EMF on

water is caused by the presence of gas/liquid microsurfaces surrounding hydrophobic impurities, in particular atomic hydrogen.

Goldsworthy, Whitney and Morris [451] investigated the effect of water treated (for up to 10 min) with a modulated radiofrequency field of 100 kHz. on the rate of reproduction of yeast cells. It was found that Treated water can either speed up or slow down reproduction depending on the duration of water irradiation and the degree of development

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addition of irradiated samples. It is assumed that EMF acts
on the double electric layer surrounding the colloidal particles.
Due to this, structured calcium is removed from the surface of biological membranes, which increases the permeability of the membranes
for free calcium, which acts as a biochemical signaling agent.

Linear changes in the specific electrical conductivity of water in a measuring cell with electrodes were observed over 30 minutes.
Stepanyan et al. in [46]. The cell was subjected to mechanical vibrations in the low-frequency range. The greatest changes in electrical conductivity were found at a frequency of 4 Hz for fresh distillate ÿ 27%, for
three-day ÿ 15%. The authors linked this effect to structural changes in the water and to gas exchange processes on the surface.
This implies that mechanical vibrations do not affect the measuring system. However, it is known [13] that the near-electrode regions of water have their own electrical properties, which can
be disrupted due to the relative displacement of the electrodes and water during
time of mechanical disturbances. Then, the conclusion that the water is entirely
changes its properties under mechanical vibrations is not entirely substantiated. In any case, in these experiments the water system showed an effect
memory with a characteristic time of tens of minutes.

5.1.2 Water-molecular clusters

Table 5.1 provides a summary of the literature data on water memory times. As can be seen, there are many studies carried out a) by different authors, b) using different methods, c) at different times in different
places, - works indicating that water retains for some time the changes induced in it by the action
EMF. Thus, *the presence of long-term memory of water is a well-established scientific fact.*

The experiments described do not contradict the hypothesis that memory
water on the EMF is associated with structural defects of water and with processes at the water/gas interface. It is especially important to observe
the action of constant and low-frequency magnetic fields on water, - electrical
component can be neglected, and the effect of the magnetic field itself on moving charges and on microscopic magnetic moments, as has been noted many times, is energetically incomparable with the effect of thermal
fluctuations. Moreover, the physical nature of water memory is also unclear.
It is therefore interesting to consider such ideas about memory mechanisms as

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Table 5.1: Relaxation of metastable states and memory of water

Impact | Property	Relaxation time
electric field | dielectric (Debye) relaxation	ÿ10ÿ11 s
photolysis | water dissociation	10ÿ4 s [221]
of magnetic fields | microwave spin-	ÿ 3 s [664]
lattice relaxation | microwave optical	tens of minutes [39]
refraction | biochemical activity of	tens of minutes [617]
microwaves | biological activity of	tens of minutes [147, 103]
RF EMF | RF EMF free radical concentration	tens of minutes [348]
| biological activity of mechanical	tens of minutes [451]
disturbances | electrical conductivity of	tens of minutes [46]
combined magnetic fields | microwave	clock [145]
luminescence spectra | spectra of conductive	clock [436]
radiation of CRTs | biological activity	clock [3]
of microwaves | microwave	clock [509]
viscosity | decrease in O2 concentration	clock [50]
of mechanical disturbances | spectrum of	clock [13]
fluctuations of ÿ radiation of organisms | corona discharge, biological activity	clock [382]
post. MP | biological activity per day [389, 623]	
comb. MP | biol. activity per day [643]	
adsorption | spin-modified water, absorption spectra	minutes–months* [115]
condensation | luminescence spectra	hours–months* [127, 536]
electrolysis | reduction and oxidation of water, biochem. activeness	minutes–months* [412]
electrolysis | stoichiometric composition	months–years* [68, 23]

*Relaxation time is highly dependent on external conditions.

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which could be verified experimentally.

The idea of existence, repeatedly renewed in literature,
structural clusters in liquid water is now receiving experimental substantiation in the works of E. Fesenko and his colleagues. Distinction
The idea in its modern form is that *macroscopic* water clusters with sizes on the order of millimetres or more are predicted.
However, the concept of a water cluster is currently undefined. It is introduced to interpret experimental data and has no specific structural, geometric, or other physical content. Therefore, it is more accurate to speak of an altered state of areas.

water or about macroscopic *metastable states* of water, -
until information about the physical nature is obtained
those changes in the properties of water that could separate one cluster from another. For such states, dynamic phenomenological models are acceptable, which take into account only the properties of the states manifested in experiments and do not determine the causes of their occurrence.
these properties. Phenomenological models, for example, thermodynamics,
are useful in the sense that they allow for targeted experimental design and the clarification or refutation of assumptions,
embedded in the model. Having been confirmed many times, the assumption
acquires the status of a scientific fact and raises the question of microscopic
the nature of its correctness.

Macroscopic states of water are characterized by immutability
certain properties throughout the entire volume of water, that is, a spatial correlation of macroscopic size. There is also a conservation of information about the properties of the state over time, that is, the property of water memory, or some coherence in time. Hypothesis

The idea that macroscopic metastable states of water and aqueous solutions exhibit quantum properties, in particular, can interfere when samples are merged, was expressed by the author in 1990
[17, 21]. This idea, which today is only a phenomenological model, at the same time allows us to predict certain results of repeatedly repeated procedures such as mixing and

dilution. It is also consistent with many known experimental data on the dynamics of water states identified,
within the framework of the model, with macroscopic quantum states. However, a review of these experiments and the development of the topic of quantum states water is beyond the scope of this book.

Let us also add that water clusters in the microscopic sense, as
more or less stable aggregates of water molecules in a liquid matrix

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water, have no direct spectroscopic confirmation to date. They exist only as isolated formations from the liquid, for example, in a molecular jet of water. Such clusters have
characteristic spectra. For example, in [705] the spectral
a band near 81 cmÿ1, which is attributed to certain vibrations
pentamer of water, a ring-shaped cluster of five water molecules held together by hydrogen bonds so that the oxygen atoms lie approximately in the same plane. The spectral band is thought to be due to tunneling of protons not involved in hydrogen bonds.

bonds, from one side of the ring plane to the other, or with twisting and bending of the oxygen core of the cluster. Note that no
features near 81 cmÿ1, as well as at other frequencies characteristic of n-dimensional water clusters [535], in the dielectric spectra
There is no permeability of liquid water. Therefore, it is difficult to talk about the existence of low-dimensional clusters in liquid water as real objects that differ in properties from the rest of the water matrix. The fact is that the interaction energy of a low-dimensional cluster is of the order of 2n, in units of hydrogen bond energy. This is the number of bonds with surrounding water molecules. At the same time, the cluster energy, binding it into a single whole is obviously two times smaller. Therefore, the environment tears such a cluster apart. Indeed, computer simulations of liquid water within the framework of the molecular dynamics method or the Monte Carlo method, see, for example, [274], reveal such clusters only as virtual constructions with
lifetime of the order of the dielectric relaxation time.

Cluster structures, predominantly pentamers and to a lesser extent degrees hexamers, become more stable near hydrophobic objects, some ions and molecular groups [535]. The interaction of the environment with the hydrophobe seems to stabilize the first coordination of water molecules around the hydrophobe. In this case, the tetrahedral coordination of the hydrogen bond network is disrupted, and the most energetically favorable configuration of water molecules in the near coordination
The sphere consists of adjacent five- and six-membered rings (at the oxygen atoms). Such are, for example, the clathrate cavities around the molecules of noble gases.

On the one hand, such clusters have nothing in common with the hypothetical clustering of liquid water itself. However, on the other
On the other hand, various stable hydrophobic hydration motifs could would be carriers of water memory. They have almost equal energy, and transitions between them are difficult due to the high barrier to generalization.

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the specified transition coordinate.

Violation of the tetrahedral coordination of the hydrogen bond network there is a violation expressed by other, complementary, concepts Bernal-Fowler rules. Therefore, generally speaking, hydration can be would be considered in terms of defects in the structure of water, and memory waters attributed to stable associates of such defects.

5.1.3 Stoichiometric composition and metastability water

Below we consider metastable states of liquid water, developing the theme of associates. They are associated with stable changes in the organization of structural defects in water. These changes are probably sensitive to the influence of external EMFs [23]. The existence of such states, as shown below, are verifiable in relatively simple independent experiments.

Water structural defects

The structural organization of oxygen and hydrogen atoms in the network of hydrogen bonds is described by the well-known Bernal–Fowler rules [284]. According to these rules: a) there are two hydrogen atoms near each oxygen atom; b) on each hydrogen bond (O–O lines) there is one hydrogen atom.3 The process of dissociation of water molecules in liquid water leads to the presence of some equilibrium level hydroxyl ions OHÿ and hydronium ions OH+

$$2H_2O \rightleftharpoons OH^- + OH_3^+ \quad (3).$$

The equilibrium concentration at T = 300K corresponds to the value pH ÿ 7 and is equal to ÿ 10ÿ7 M/l. The appearance of OHÿ and OH+ ions violates rule a), so-called ionic defects of the water structure arise. There are also defects associated with the violation of rule b). They are called Bjerrum's orientational defects: The D-defect corresponds two protons on the O–O line and an L-defect—the absence of protons on O–O lines [221], Fig. 5.2. These defects arise due to the disruption of the correct orientation of the water molecule in the network of hydrogen bonds

$$2N \rightleftharpoons D + L,$$

3The Bernal-Fowler rules are well defined for ice. We use these rules and related concepts for liquid water to illustrate processes occurring on microscales of time within one or two coordination units.

spheres.

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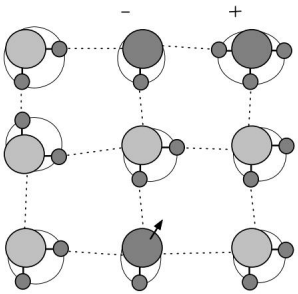


Fig. 5.2: Ionic OH^+_3, $OH^ÿ$, orientational D and L defects and defect-radical $OH^ÿ$ as a violation of the ideal structure.

where N is a defect-free hydrogen bond. An estimate of the concentration of Bjerrum defects in water < 10ÿ6 M/L is given in [408]. Bjerrum defects carry mutually opposite effective electric charges: L-defects are negative, D-defects are positive.

The equilibrium of ionic defects can be easily shifted by adding acid or alkali. The equilibrium of orientational defects is not directly is associated with ionic defects. It can probably be shifted by changing stoichiometric composition of water. This follows from rule b).

Sometimes, ionic structures of the type $(H_{2i+1}O_i)^+$, i = 1, 2, ... are identified and discussed in the hydrogen bond network of water. However, all of these structures are model forms of the hydronium ion, which exists in liquid water as a defect distributed over several water molecules. In other words, hydronium is a perturbation of the network.

hydrogen bonds due to a locally excess proton, covering a region with dimensions of the order of 10–20 Å ^{o}. The same blurriness is also characteristic of other structural defects.

The movement of defects occurs due to classical and quantum proton jumps along and between hydrogen bonds [408]. Fig. 5.3 shows the states of water molecules of the first coordination spheres during the movement of the D-defect. Such ideas about the movement of water defects due to proton jumps and rotations of molecules were used by Davydov and co-workers in the theory of solitons in molecular chains [72]. Ionic defects in the structure of water are chemically active. Literature data on the chemical activity or inactivity of orientation defects have not been found. Violation of the ionic equilibrium dissociation of water molecules relaxes in a time of about 10ÿ4 s. This the characteristic time of diffusion movement of hydronium and hydroxyl ions before the first contact leading to their recombination. It is much fewer metastable states of altered energy observed in the experiment water with a decomposition time of a month or more. Therefore, it is worth looking for other

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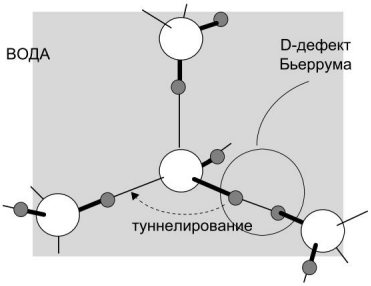


Fig. 5.3: Movement of an orientational D-defect in the network of hydrogen bonds due to tunneling proton transfer to the neighboring one connection.

mechanisms of such long-term metastability.

Mobility of water defects in a magnetic field

The mobility of water defects changes in magnetic fields due to spin effects. These are due to the propagation of proton wave functions to adjacent potential wells of the hydrogen bond network. If the adjacent the well is empty, then the “tail” of the wave function covering it determines the probability of a proton’s quantum transition into this well. For various estimates of the intensity of quantum and classical transitions of protons in the hydrogen bond network are comparable to each other. If the adjacent well is occupied by another proton, then due to the overlap of their wave functions there is a so-called exchange interaction of protons, which depends on mutual orientation of their spins. Let us consider a section of the molecular chain in Fig. 5.4, which includes a D-defect on a hydrogen bond. One of the protons of the D-defect can undergo a quantum transition along the reaction coordinate x. The potential energy of the proton has a characteristic double-well type. The two outer particles are considered fixed. The complex interaction of the mobile proton with the stationary ones includes an exchange energy that depends on the relative orientation of the spins. Fig. 5.4 shows the change in the double-well potential for different orientations a), b) and c) of the proton spins. If the extreme spins are oppositely directed, the potential becomes asymmetric. The probability quantum transitions of a proton from well to well depends on the type of potential.

There is some thermal level of transition intensity without taking into account the exchange interaction. The magneto-dependent contribution to the transition intensity is, in the first approximation, proportional to the magnitude of the overlap integral of the proton wave functions and is assumed to be sufficient for observation. This contribution is modulated by the mutual state of spins that evolves in an external magnetic field.

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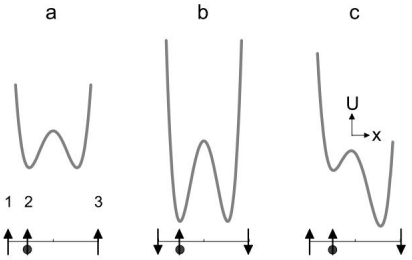


Fig. 5.4: Nature of dependence potential energy of the tunneling proton of the D-defect from spin states of the triplet of spin-new

The spins can be controlled using an external magnetic field. It is interesting that the energy of the system remains practically unchanged due to the relative smallness of the magnetic interaction energy. At the same time,
transition probabilities change, which leads to a change in the overall mobility of water defects.

The Hamiltonian of the model system includes orbital, Zeeman, magnetic dipole-dipole, exchange energies, the effective potential of the electron shell, as well as the relaxation interaction with the thermostat:

$$H = \frac{1}{2M} P(2) - \frac{e}{c} A(t) \quad \ddot{y}\,\ddot{y}\, I(1) \quad + I(2) \quad + I(3)\, H(t) +$$

$$+ \sum_{\ddot{y},\ddot{y}} Hdd\, I(\ddot{y}) \quad , I(\ddot{y}) \quad + \sum_{\ddot{y},\ddot{y}} Hexch\, I(\ddot{y}) \quad , I(\ddot{y}) \quad + U\, x(2) + Hrelax \quad ,$$

where the superscript in brackets numbers the particles. Two adjacent spins form two-particle singlet-triplet states ÿ due to the exchange interaction, and the third one forms a single-particle state ÿ. By denoting by ÿ(x) the orbital functions of the proton in one of the wells, we can immediately
write down the approximate eigenfunctions of the Hamiltonian unperturbed by magnetic and thermal interactions

$$\ddot{y}0 = \frac{1}{\ddot{y}2} \quad \ddot{y}(x)\ddot{y}(1)\ddot{y}(23) \pm \ddot{y}(\ddot{y}x)\ddot{y}(12)\ddot{y}(3) .$$

It is clear that these functions do not factor into a product of functions.
only spatial and only spin variables; in such cases, we speak of “entangled” quantum states. This means
the presence of some effective interaction between the coordinate
proton and the spin state of the system, - interactions that
can be controlled by turning on magnetic disturbance, that is, by changing the spin-

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a new state by an external magnetic field. In this case, the probability of the particle transition from hole to hole changes. Numerical calculations of this model are given in [23].

Deviations from the correct stoichiometry of water

One of the possible mechanisms of water memory is the disruption
stoichiometric composition of water. Let's consider it using the example of an electrolyzer with a semipermeable membrane separating the cathode and anode regions. The violation of the stoichiometry of the water composition occurs due to the release of H2 and O2 gases at the cathode and anode, respectively, and due to complex processes on the membrane. It is logical to assume that
the membrane is more permeable to some types of charge carriers and less
permeable to others. The electroneutrality of the fractions is ensured by a corresponding change in the concentration of hydrated electrons,
Fig. 5.5. The formula for the metastable state of water in this case is
there is a view

$$H2+x\ Oe\ddot{y}_{x}, \qquad (5.1)$$

where x is the concentration of hydrated electrons per water molecule. Relaxation of the metastable state after water is withdrawn from the electrolyzer is obviously extremely difficult, since it can only occur through gas exchange on the water surface. Under normal conditions, the partial pressures of oxygen and hydrogen in the atmosphere differ greatly. Therefore, the relaxation of the catholyte and anolyte

fractions with different signs of x will occur at different rates. Negative values of x should be understood as a deficiency of electrons, that is, a corresponding number of ion-radicals. The removal
hydrogen atom from a water molecule leaves an electrically neutral
OHÿ radical ion. In this case, the formula of the metastable state
has a different appearance

$$H2\ddot{y}x\ O(OH)_{x}, \quad \text{or } H2\ O1+x\ .$$

The formation of water with altered stoichiometry is a consequence
maintaining a certain balance in the process of charge and mass transfer
through the membrane. We assume that carriers of different types participate in the membrane conductivity: ionic $OiH(k\ddot{y}2i)_{k}$, where the charge of the ion is indicated in brackets, electron eÿ and oxygen ion-radical Oÿ ÿ. Ion carrier notation
charge in this form includes both molecular ions such as hydronium and hydroxyl, and atomic ions such as H+ and O2ÿ. Neutral
hydroxyl radical OHÿ cuts the , obviously, does not participate in the charge transfer membrane.

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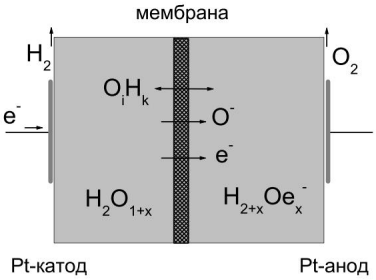


Fig. 5.5: Electrolysis of water and formation of metastable states of water with altered stoichiometry in an electrolyzer with membrane.

The law of conservation of total current in a circuit requires that it be equal to the amount of charge passing through the cathode, membrane, and anode per unit of time in steady state. For simplicity, we'll choose the interval time ÿ during which a charge passes through any cross-section of the circuit one electron. Let p denote the probability of an electron passing through the membrane towards the anode in time ÿ. For the ion-radical and for different hydroions we denote this probability by pr and pik accordingly. We can write down the charge that passed through the membrane and equal to ÿe, in the following form

$$e(k ÿ 2i)pik ÿ epr ÿ ep = ÿe,$$

summation over all i, k. This yields the expression that will be needed below.

$$kpik = pr + p ÿ 1+2ipik . \qquad (5.2)$$

Before writing down the expressions for the flows of matter, let us recall that reactions occur at the electrodes with the release of molecular gases

$$\text{cathode: } OH+ \quad {}_3 \; +eÿ ÿ H2O+ \quad \frac{1}{2}H2 ÿ$$

$$\text{anode: } OHÿ ÿ eÿ ÿ \quad \frac{1}{2}H2O+ 4 \; \frac{1}{}O2 ÿ ,$$

That is, for every electron that passes through, a hydrogen atom is removed from the catholyte region, and half an oxygen atom from the anolyte region. Taking this into account, we find that for every electron that comes from the catholyte region, the region is leaving

$$ipik + pr O+ kpik +1 H .$$

After substituting (5.2) and simple transformations, we find the final expression for the loss of substance from the catholyte fraction. Similarly

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we also find the gain of the substance in the anolyte fraction. These are the ratios
niya:

decreases from the catholyte: ipik + pr H2O+ ÿH , (5.3)

arrives in anolyte: ipik + pr ÿ 2 $\frac{1}{-}$ H2O+ ÿH ,

ÿ = p ÿ pr .

If p>pr, which is plausible due to the larger size of the ion-radical,
then ÿ> 0 and the catholyte is depleted of protons. Conversely, the anolyte is depleted of protons.
is enriched. The mass balance throughout the liquid, as it should be, is negative.
Summing up the relations (5.3) with the corresponding signs,
we find that the liquid loses for every electron that passes through the chain
half a water molecule. It is released at the electrodes in the form of molecular gases.

It should be noted that protons do not transfer from the catholyte to the anolyte, and there are no changes in stoichiometry within the framework of this mechanism, unless the electron and ion-radical contributions to the membrane conductivity are taken into account. In the initial stage of electrolysis, these charge carriers are practically absent in the water, since their appearance is associated with the rupture of covalent O-H bonds. The intrinsic conductivity of the membrane is low compared to
ionic conductivity of liquid water and the entire potential difference of the anode–
the cathode falls on the membrane. If it is thin enough, and the applied
If the voltage, on the contrary, is high, then the field strength in the membrane
reaches significant values. The process begins in the pores of the membranes
ionization of water molecules, at E ÿ 106–107 V/m,

H2O ÿ O2ÿ + 2H+ ,
O2ÿ ÿ Oÿ ÿ +eÿ ,

which leads to the emergence of electronic conductivity. In the area
anolyte electron is present in hydrated form, providing
electroneutrality of the anolyte fraction enriched in protons, then
that is, atomic hydrogen. This diagram is an illustration of the processes that
change the stoichiometric composition of water. A more complete consideration
could be based on plasma equations with chemical reactions, which are quite
convenient for study in this quasi-one-dimensional
case.

Thus, the catholyte fraction is characterized by a decrease in the relative number of protons, an alkaline reaction and, probably, a high content of dissolved molecules.

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polar hydrogen. The anolyte fraction has an acidic reaction, an increased content of protons and dissolved
molecular oxygen.

Interestingly, the hypothesis of non-stoichiometric water is testable experiment. The value x in formula (5.1) is measurable by NMR on water pre-enriched with 17O isotopes. To do this, it is necessary to obtain the ratio of NMR signals from protons and from 17O nuclei. This value, obviously,
but is proportional to the ratio of the numbers of hydrogen and oxygen nuclei in water, and the proportionality coefficient c depends only on the properties device

$$W = c \quad \frac{NH}{NO} \ .$$

For anolyte, as follows from (5.1), it is equal to Wa = c(2 + x), and for catholyte Wk = c(2 ÿ x). The quotient depends only on the parameter x

$$\frac{Wa}{Wk} = \frac{2+ x}{2 \ddot{y} x} \ . \qquad (5.4)$$

The deviation of this experimentally measurable ratio from unity, i.e. x = 0, cannot be explained otherwise than as a deviation from the stoichiometric composition of water. Another prediction within the framework of the discussion
The mechanism is based on the dependence of the relaxation rate of the altered state on gas exchange on the water surface. In particular, such
water is preserved indefinitely if it is contained in a vessel with walls impermeable to hydrogen.

■ The presence of structural defects in liquid water at equilibrium is determined by the natural level of unlikely thermally activated processes of molecular dissociation and rotation of molecules into energetically unfavorable metastable positions. As already mentioned, the appearance of defects can be explained by violations of Bernal's rules.

Fowler. An essential condition for the operation of the rules themselves is the ideal stoichiometric composition of water, expressed by the formula H2O. The possibility of the appearance of structural defects in water due to a violation of the stoichiometric composition of water has not previously been discussed in the literature. In this case, the concentration of defects would be,
obviously proportional to the deviation from the stoichiometric composition multiplied by Avogadro's number, that is, it is unusually large.

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Hydroaeroions and water stoichiometry

It is interesting to connect the well-known phenomenon of biological activity of hydro-aeroions with the deviation of the formula of water from H2O. The beneficial effect of negative aeroions on living organisms, discovered A.L. Chizhevsky, have been studying them for more than half a century [49]. The mechanism of their therapeutic and biological action on model systems is completely has not been clarified. One hypothesis links the effect to the influx of electrical charge introduced by ions into living tissue, while others start immediately with level of biochemical kinetics. Changes in the structure of the aquatic environment caused by hydroaeroions as the primary cause of further biochemical transformations are also not without foundation. The entry of the OHÿ aeroion into water due to the relatively rapid removal of excess electrons is equivalent to the addition of a neutral OHÿ radical to water, or, which is obviously due to the removal of the neutral Hÿ atom-radical from water. The resulting structural defect in water, associated with a deviation from stoichiometry, is very similar to the Bjerrum L-defect. It is different from the latter is formed by the absence of a proton between the molecule water and the OHÿ radical rather than between two water molecules. This leads to a decrease in the mobility of such a defect, since the mobility of due to purely proton exchange is impossible. The recombination rate of 2 OHÿ ÿ H2O2 radicals , relatively low due to the Coulomb repulsion of the L-defects associated with them, is further reduced due to their low mobility. At the same time, the chemically active radical OHÿ capable of entering into reactions of the next level. Acquisition by water biological activity due to its physical activation was associated with the appearance of OHÿ radicals in [111].

Let us estimate the number of added defects, assuming that the solution absorbs all air ions falling on its surface. Taking the surface area of the solution S = 1 cm2, the flow velocity V = 102 cm sÿ1, the concentration of ions in the flow c = 2.5 105 cmÿ3 and the blowing time t = 102 s, [49], we obtain n ÿ cV St ÿ 2.5 · 109. This number of defects per volume of solution of several milliliters approaches the endogenous concentrations of enzymes, corresponds to the equilibrium concentrations of water defects and is therefore capable of producing a noticeable effect if consider Bjerrum defects and/or OHÿ radicals to be chemically active. Water treated with OHÿ aeroions is similar to the catholyte fraction water from an electrochemical cell with a membrane. The deviation from stoichiometry in both cases occurs towards depletion of protons H_2O_{1+x}, $x > 0$. Therefore, since negative hydroaeroions have a positive therapeutic

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effect, then catholyte water should have a similar effect.
Excess L-defects of the catholyte, carrying an effective negative charge, bind positively charged hydronium ions,
due to this, they increase the pH value and additionally shift biochemical equilibria involving hydrogen.

■ The stoichiometric composition of water is hardly disturbed or is disturbed only slowly when other molecules consisting only of water are dissolved in it.
from oxygen and hydrogen, such as molecular gases or peroxide
hydrogen. The rupture of molecular covalent bonds, which are much
stronger than hydrogen, achievable by appropriate heating of such a solution
or long-term storage. In [111] it was believed that the addition of hydrogen peroxide H2O2 leads to the emergence of biological activity
water due to the dissociation of peroxide molecules with the formation of radicals. The natural relaxation time of the broken stoichiometric
equilibrium

$$H_2O_{1+x}\ H_2O_2,\ H_2,\ O_2$$

in this case is relatively large. At the same time, the breaking of covalent bonds by an electric field, outside the water sample, in the case of blowing
hydroaeroions or inside the sample, on the membrane, which is technically simpler and is carried out relatively quickly. Probably, the action of magnetic
fields, discussed in the previous section, are capable of shifting the meta-stable stoichiometric equilibrium of water by changing the mobility of water defects and thus inducing biological activity of water.

Research using hydroaeroions on 2H and 2H isotopes
17O are able to reveal the role of spin degrees of freedom in processes
incorporation of aeroions into the network of hydrogen bonds of water. Also, if
the primary mechanism of action of hydroaeroions, associated with the violation of stoichiometry, is correct, then the mixing of treated water with
incubation mixture should have qualitatively equal consequences
using an incubation mixture treated with ions directly.

Experiments on water electrolysis

It is known that free radical oxidants such as the hydroxyl radical OHÿ and hydrogen peroxide H2O2, which dissociates
with the formation of these radicals, the superoxide anion radical Oÿ ÿ 2 And
Electronically excited singlet oxygen 1O2 causes the destruction of protein macromolecules, lipids, DNA, enzymes, and leads to

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various diseases [89]. In the work [412] Shirahata et al. used a standard electrolyzer to obtain and study
water samples with antioxidant activity from purified and salted water with 0.1 g/l NaCl. The electrolyzer device is not
was explained, however, the measured properties of the fractions are comparable with the properties of the catholyte and anolyte fractions discussed above membrane electrolyzer.

The fraction of water near the cathode after sufficient treatment had an alkaline reaction pH ÿ 10–11, an increased concentration
dissolved molecular hydrogen H2 0.45–0.55 mg/l, low concentration of dissolved oxygen O2 3.4–3.6 mg/l and large negative values of redox potential ÿ600–800 mV.

This water also had specific antioxidant activity, which was determined by biochemical methods, Fig. 5.6. At the same time
no specific activity arose after saturation of water with molecular hydrogen, instead of electrolysis, which indicated that
that the activity is due to some independent quality of the liquid
water. Shirahata et al. believed that the antioxidant activity of reduced water, or catholyte, was due to the increased concentration of atomic hydrogen. The only argument in favor of this conclusion was that the activity disappeared after autoclaving.

in the presence of tungsten trioxide WO3, an effective absorber
atomic hydrogen.

Note that in the above diagram of the membrane electrolyzer Fig. 5.5, abstract biological activity of catholyte was associated
with a reduced, rather than increased, content of protons in water, while
while other characteristics of the catholyte, pH and dissolved molecular hydrogen, correspond to reduced water [412]. It is not yet clear what this discrepancy is due to. The concentration of atomic hydrogen in a direct experiment is immeasurable; the author is not aware of the corresponding experimental methods. Atomic hydrogen, unlike

molecular, it is impossible to represent it as a separate chemical
substance dissolved in a matrix of "normal" water H2O. As already
It was said that due to the intense proton exchange, atomic hydrogen is so tightly embedded in the network of hydrogen bonds that it forms a single whole with it and with the aqueous medium. This is reflected in the formulas
non-stoichiometric water, catholyte H2O1+x and anolyte H2+xOex. Perhaps the ideas [412] about the processes in an autoclave involving salts
and oxides and, especially, the concentration of dissolved atomic hydrogen in liquid water need to be clarified. It is also possible that

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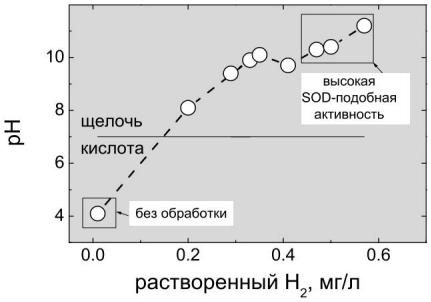


Fig. 5.6: Dependence of the hydrogen index of the reduced
water from the concentration of the solution
renated molecular hydrogen,
constructed based on data from [412].

dependence of the specific activity of water on the proton content
has a substantially nonlinear character.

Thus, the change in the structural properties of water under the action of
weak magnetic field is probably associated with the exchange interaction of protons in liquid water. Treatment with EM fields leads to a change in the mobility of water structural defects —ionic, orientational, and free radical types—and shifts the biologically significant

metastable equilibrium of various types of water defects, expressed in the violation of its stoichiometric composition.

■ Defects in the structure of water, and the proton subsystem of water in general, are attractive in the search for a target for EMF action. The following are relevant for this: compelling arguments:

— the contribution to the magnetic Hamiltonian of the proton from the spin magnetic moment exceeds the contribution from the orbital magnetic moment,
— the spin mechanical moment of the proton is the same as that of the electron. Electron spins, participating in the exchange interaction, play
a crucial role in chemical reactions. It is likely that the exchange interaction of protons partly determines the mobility of structural defects.
water, creating a contribution to kinetic phenomena in solutions,
— protons are a component of water, the environment in which biochemical processes occur, and at the same time a reagent, a participant in many biochemical reactions,

- unlike free radicals, the number of protons in water
huge,
— proton spins relax very slowly, within seconds, and therefore have enough time to adjust or “feel” the external EMF.

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5.2 Biological effects of microwaves and ion interference

The development of research into the biological effects of mm microwaves is associated with the creation of generators of electromagnetic oscillations in this range. In the USSR, such research began in the 1960s and 1970s under the leadership of Academician Devyatkov [75, 58, 77]. Some of the first foreign works in this direction were those of Webb and Dodds [716] and Webb and Booth [715] The main features of the biological effects of microwaves of non-thermal intensity are well known [58, 307, 16]:

- resonant, spectral nature of the response of biological systems to non-thermal, < 1 mW/cm2, microwave radiation, resonance width 10ÿ2–10ÿ3 from the maximum resonance frequency,
- resonant nature of the response depending on the frequency of the module-microwaves,
- weak dependence of the effect on the radiation power, often starting from a certain threshold power,
- the presence of physiological windows of effect, the dependence of spectra on the type of biological system and its physiological state.

The non-thermal nature of the effects follows from the presence of resonances and from that biological responses to microwaves and heating often have opposite direction, see, for example, [715, 157, 168]. The biological effects of ultra-low intensity microwaves [463, 635] are also difficult to link with thermal effects. Bibliography from the resonant non-thermal effects of millimeter-wave radiation one can find, for example, in the monograph by Devyatkov, Golant and Betsky [78], in reviews Miller [574] and Betsky [286], in the reference book of Polk and Postov [468] and There is a published Internet hyperlink database [571] devoted to various aspects of the topic, primarily in connection with the potential health risks to cell phone users.

5.2.1 Spectral measurements

Frequency spectra of millimeter waves are the most informative in terms of primary mechanisms. However, such observations, with any detailed frequency scanning, are relatively few in number, as they require a great deal of time. Moreover,

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The most valuable spectral information lies in the spectral shifts that occur when the experimental conditions change.

The frequency-selective action of microwaves is observed both on living systems and on proteins *in vitro.* Devyatkov, Khrapov et al. in their work [47] and Devyatkov in their review [76] indicate that under the influence of microwave radiation the state of the Fe2+ ion in the heme oxy-form changes
hemoglobin Hb. According to Mössbauer spectra on the isotope 57Fe, it was revealed that some of the iron ions in hemoglobin transition from a low-spin, S = 0, to a high-spin, S = 2, state. The effect had
frequency selectivity, and the sign of the effect changed depending on the frequency, which indicated a non-thermal mechanism of action
microwaves. The data were confirmed by Didenko, Zelentsov, and others.
[98] In this work, the resonance width was measured near 42.173 GHz.
at a power of 4 mW/cm2 and long-term stability of the generator
worse than 1.3 MHz. The magnitude of changes in the parameters of the Mössbauer spectra was about 15%. After an hour of exposure to microwaves, the effect relaxed within a few hours. It was discovered
several effective frequencies, and at different frequencies the effect of bearing forces is generally of different qualitative nature. This indicates that
microwave targets within a single macromolecule can
may vary depending on the frequency of exposure.

Webb [713] found that lambda prophage synthesis in E. coli cells was inhibited by unmodulated microwave EMF.
strongly depended on the frequency and power of the field and on the amount of oxygen in the environment. A 105-fold increase was recorded under optimal conditions.
70.4 GHz and 0.25 mW/cm2. At a power of 0.6 mW/cm2, the effect decreased in ten times. The resonance width was ÿ 200 MHz.

Bannikov and Rozhkov [12] investigated the frequency dependence of the effect of millimeter waves on E. coli cells. They measured the induction
phage ÿ by the *E. coli* K-12(ÿ) strain. The energy flux density was
0.1–0.2 mW/cm2. About 30 effective frequencies were found in the 40–60 GHz range. The spectral peak at 41.268 GHz had a width
about 1 MHz.

Grundler and Kelman [464], Grundler, Kaiser et al. [568], and Grundler and Kaiser [463] observed resonant peaks in the growth of yeast cells under radiation conditions in the region of 41.7 GHz. In [464], they obtained
frequency spectrum of the effect of microwaves on the growth of *Saccharomyces* cells *cerevisiae* in the range of 41.65–41.83 GHz. The spectrum consisted of many spectral peaks about 8 MHz wide, separated by intervals
around 16 MHz. The use of different radiating antennas gave

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Spectra that match with an accuracy of 1 MHz. The power threshold for the bio-effect was measured near 1 mW/cm2. The generator's emission band was about 1 MHz.

Andreev, Bely and Sitko in their work [8] found that microwave radiation in the range of 52.6–53.8 GHz with a power of the order of
mW/cm2, when applied to specific acupuncture points on the human body, causes significant changes in the bioelectrical activity of muscles in other parts of the body. This effect was found to be frequency-selective. Several spectral peaks with a width of approximately 100–200 MHz were recorded in this range.

Aarholt, Jaberansari et al. in [587] reported that 18–20 hours of exposure to 2 GHz modulated EMF with a power of the order of
1 ÿW/cm2 caused cataract formation (clouding of the lens) in the prepared pupils of animals *in vitro.* The modulation frequency corresponded to 1H NMR, i.e., 2.13 kHz in the geomagnetic field.
50 ÿT. The effect had frequency selectivity both in frequency
carrier and modulation frequency. Radiation at a frequency of 55 MHz with a bandwidth of 50 Hz caused cataracts when the power was attenuated to 7.5 nW/cm2.

Belyaev et al. [428] measured the peaks of the resonant response of E. coli cells to microwave radiation of 0.1 nW/cm2 at frequencies
41.324±0.001 GHz and 51.765±0.002 GHz. The introduction of various prophages into the bacterial chromosome caused a frequency shift of resonances up to 0.05 GHz.

On the frequency-dependent action of microwaves in the range of 38–78 GHz on ion currents in the membrane of seaweed were reported by Kataev et al. work [206]. Hourly exposure to microwaves with a power of 5 mW/cm2 caused a 100% decrease in Clÿ ion currents at frequencies of 41, 50, and 71 GHz and the same order of magnitude increase when deviating from these frequencies by ÿ 1 GHz. It is assumed that the microwave targets are not ionic channels, and some links in the chain of biochemical regulation of channels. At the same time, a slow change in the concentration of the channel control agent depends on the radiation parameters.

Gapeev, Chemeris et al. in [168] showed that meander-modulated microwave radiation affects the motor activity of *Paramecium caudatum* cells . The effect was resonant in nature with
spectral peak in the center of the range 42.0–42.5 GHz. The emission bandwidth was 10–20 MHz. Gapeev, Safronova, and others studied in [138] the frequency spectra of microwave action in the frequency range
41.5–42.7 GHz and a wide range of radiation powers at different

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configurations of emitters and observed several peaks of action
on the activity of mouse neutrophils.

In the work of Rubin, Lukashev et al. [56] spectral selectivity
No effect of EMF in the range of 54–78 GHz on charge transfer in light-sensitive
pigment-protein complexes was detected.
However, the action depended on the mutual polarization of the acting and
probing radiation, which allowed the authors to assume the non-thermal nature
of the observed effect. It is likely that these molecular processes underlie the
observations of the effects of microwave radiation on photosynthetic organisms
at the biological level, which are shown
in the work of Tambiev and Kirikova [688].

Power windows in the biological effects of microwaves have also been
reported. Adie, in a review [220], reports that the effect of radiation
450 MHz with 16 Hz modulation on the output of labeled calcium ions from the
hemispheres of the chicken brain reached a maximum at a power of 1 mW/cm2
with variation in the range of 0.05–5 mW/cm2. Dutta, Subramoniam and
others in [572] found power windows during microwave irradiation of brain tissue.
In a culture of nerve cells, the outflow of calcium ions during irradiation with 915
MHz EMF increased with a specific absorption power
0.05 and 1.0 mW/g. This effect did not occur at either lower or higher irradiation
powers and depended on the presence of low-frequency modulation. The
parameters of the Mössbauer spectrum of polycrystalline rabbit hemoglobin
enriched with the 57Fe isotope were determined
at a temperature of 77 K Didenko, Zelentsov et al. in the work [91]. The frequency
The Gunn diode oscillator frequency was 42346.70±0.01 MHz with an instability
of ÿ2.5 10ÿ8. A window in radiation power was found in the range of 0.5–2 mW/
cm2. The lower threshold was explained by the competition between the
processes of accumulation and dissipation of acoustic mode energy, the upper one –
nonlinearity of these processes. In [635] Belyaev, Shcheglov et al. showed the
effect of 51.674 GHz radiation on the conformational state of the genome
coli at a certain density of cell suspension in
range of 10ÿ11–1 ÿW/cm2. The absence of
effect at higher radiation power.

5.2.2 Theoretical concepts

There are many hypotheses in the scientific literature about the physical nature
biological action of microwaves. However, despite the fact that microwave radiation quanta
are only one to three orders of magnitude smaller than the thermal scale ÿT, there are no
clearly established and recognized mechanisms of such action by the physics community.
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several examples in which the following were used for explanation
ideas.

High-Q molecular, subcellular and cellular oscillators

The frequency, wavelength and propagation speed of elastic vibrations (sound) in biological tissues are related by a simple relationship
fÿ = v ÿ 105 cm/s. Therefore, various biophysical structures, cells, organelles, membranes and large macromolecules with dimensions of 10ÿ5–10ÿ6 cm and considered as elastic elements, are resonators of a suitable frequency range of 1010–

1011 Hz. This fact was used from the very beginning as a possible explanation for the biological effects of microwaves. In this case, they considered
Resonators carrying an electric dipole moment. This ensured the "coupling" of microwaves with the resonator's oscillations.

Discussing the possible mechanism of action of microwaves on hemoglobin, Chernavsky suggested [207] that microwaves excite oscillations
protein, accumulating in the form of elastic deformation of a single generalized degree of freedom covering the entire protein (the concept of “protein–
machine"). The natural frequency is estimated to be around 100 GHz. Modified
the state of the protein entails a biological response.

Smolyanskaya, Gelvich et al. [169] suggested that the effect of microwaves on the rotational states of molecular segments such as
OH groups and amino acid radicals are the most likely explanation for the acute resonance effects of microwaves in biological systems. This paper also provides a brief overview of early ideas about the mechanisms of the biological action of microwaves. In particular,

The emergence of mechanical forces in a heterogeneous medium is discussed
inhomogeneous electromagnetic field: there is no frequency selectivity.

Sometimes the frequency spectra of responses to microwave radiation
look like the teeth of a comb, forming a more or less regular series of effective frequencies, [464]. This gives rise to the idea of classical multi-mode resonant systems, often discussed in the literature. For example, Golant [63] substantiated the fact that such multi-mode high-Q oscillators can be cell membranes and their

areas. In a normal state, they emit EM waves of the spectrum of natural frequencies of self-oscillations in the millimeter range - self-oscillations excited by metabolic processes. EMFs of this range serve as natural regulatory signals in intra- and inter-

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cellular interactions. Special external weak electromagnetic fields introduce synchronization into electromagnetic information exchange and cause a variety of biological responses. This mechanism explains the resonant nature of the responses and the presence of a threshold dependence with saturation of the biological effect on the EMF power.

Difficulties in the mechanisms of direct action of microwaves on dipoles resonators are probably due to the significant damping of their oscillations, which prevents the accumulation of any significant
energy of such oscillations. Dipole d in EP E experiences a force Ed/R stretching or compression depending on the relative direction of the field vector and the dipole moment, R is the size of the dipole. Let M be the mass
dipole. The generalized coordinate r of the dipole oscillates in a variable field E cos ÿt. For the dimensionless coordinate x = r/R we can write equation of a damped linear oscillator

$$x^{\cdot\cdot} + \ddot{y}x\ddot{y} + \ddot{y}2\ 0x = \cos \ddot{y}t\frac{Ed}{MR2} \quad ,$$

where ÿ0 is the natural frequency of the oscillator. It is easy to find that under resonance conditions ÿ = ÿ0 , the amplitude a of the forced oscillations and their energy are equal

$$a = \frac{Ed}{\ddot{y}\ddot{y}MR2} \quad , \quad = \frac{M}{2}\frac{}{}(Rx\ddot{y})2 = \frac{E2d2}{4\ddot{y}2MR2} = \frac{\ddot{y}Sd2}{c\ddot{y}2MR2} \quad ,$$

where S is the microwave energy flux density (1.9). Chernavsky and Khurgin [209] estimated these values for a realistic protein macromolecule of size 5 x 10ÿ7 cm, for sound attenuation of ÿ107 sÿ1 and S ÿ
1 mW/cm2. The oscillation energy was ÿ 10ÿ20 erg, which is almost
seven orders of magnitude below the thermal scale ÿT at physiological temperatures. The fact that biological effects of microwaves are observed at much lower radiation powers than those included in the assessment devalues the discussion of the mechanisms associated with the accumulation of microwave energy.

Collective excitations of multiparticle systems

Davydov and his co-workers [72] investigated the energy transfer of intramolecular vibrations along the ÿ-helical region of a protein macromolecule. It was shown that the energy transfer of C=O vibrations of peptide
groups is effectively carried out by soliton excitations that deform the molecule, see Appendix 6.6. It is believed that the energy

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hydrolysis of ATP molecules, which is widely used in the body, can
be delivered to the point of consumption by another reaction in the form of a C=O
vibration carried by a soliton. There are also other collective excitations of the
macromolecule, of the exciton type. Excitons, propagating, excite phonons and
therefore quickly decay. They do not
can be effective carriers of ATP energy quanta. Davydov and Eremko [74] and
Eremko [86] showed that an external electromagnetic field of the resonant
frequency of the millimeter wave range causes dissociation
soliton on a rapidly relaxing exciton and local deformation
protein molecule. This disrupts the efficiency of hydrolysis energy transfer and
causes a biological response.

A brief overview of the biological effects of microwaves from the point of view of
The phenomenon underlying them, proposed by Fröhlich [441] - coherent
excitations of dipole structures - is presented in the work of Hyland [477].
Coherence means, as usual, the conservation of the relative phase (phase
difference) of oscillations separated in time or space. An illustration of this
phenomenon is as follows. Coherent excitations of ordered dielectrics in biophysical
structures arise as a result of the electric dipole interaction of the molecules that
form these structures. Depending on the magnitude of the intermolecular dipole-
dipole interaction at room temperature, only the lowest energy collective oscillations
can be excited. Moreover, the statistics of such excitations are significantly

differs from the Boltzmann distribution. It follows the Bose-Einstein distribution. In
such systems, as the temperature decreases below
At a certain critical point, called the degeneracy temperature, a phase transition,
Bose condensation, occurs, when the energy of the oscillations begins to shift to
a lower vibrational mode. The stronger the interaction between the dipoles, the
higher the degeneracy temperature. An external electromagnetic field seems to
enhance the interaction between the dipoles. It partially synchronizes the individual
oscillations; the dipoles become phased, as a result of which the energy also
increases.
their interaction. If the external stimulus is strong enough, the degeneracy
temperature becomes higher than room temperature, which leads to condensation.
The oscillation of the dipoles becomes completely coherent—a macroscopic
oscillation of the dipole ensemble arises. It is postulated that
that it causes the biological effect. Computer modeling by Pokorny [607] showed
that energy can accumulate in several macroscopic vibrational states.

The model predicts frequency selectivity and the presence of a threshold.

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microwave power to achieve the effect.

Davydov [71] pointed out the lack of clarity in the mechanism of communication of the collective excitations of this type with the vital activity of the cell. It is not obvious that microscopically localized biochemical process is sensitive to the presence of synchronously oscillating dipoles far from the reaction site. Chernavsky and Khurgin [209] noted that microwave power
ÿ1 mW/cm2 with realistic attenuation values are capable of exciting only /hf ÿ 10ÿ4–10ÿ5 additional quanta of collective elastic modes (see p. 437), which raises doubts about the effectiveness
control of intermode transitions using microwave radiation. At the same time, Fröhlich [442] notes that the source of energy external to the dipoles may be metabolic energy.

If the flow of this energy is large enough, then the system is close to the point phase transition. Then even a small increase in flow, for example, for due to the external EM field, will cause a transition to a coherent state. The author of this book was unable to find any works in which this was experimentally, in in any specially prepared artificial dipole medium, the condensation of collective dipole excitations would be clearly observed.

Blinovska, Lech and Wittlin [326] showed that the absorption spectra Microwave spectra of 35.5–37 GHz, containing several extrema, are virtually identical for solutions of erythrocytes and their membranes. It was suggested that the spectra are associated with the collective oscillations postulated by Fröhlich, which in this case are localized in the cell membranes.

The Davydov and Frohlich models are provided with some correspondence with independent experimental studies, - Raman scattering spectra on microorganisms. At the same time, hypotheses,
The assumptions underlying these models have not yet received the status of reliably established scientific facts.

Bohr, Brunak and Bohr [577] considered the mechanism of action of microwaves, associated with special excitations in biopolymer macromolecules, such as DNA. Such molecules are often characterized
energy density of bending and twisting. In the continuum approximation, excitations of the DNA double helix are torsional vibrations with natural frequencies, according to the authors' estimates, in the region
12 GHz with a bandwidth from 10 MHz to 10 GHz. Initiation of interaction of torsional and bending modes by external EMF can lead to,
due to the topological properties of the chain, to the localization of the bend due to unwinding and, consequently, to the rupture of the molecule. It is assumed that

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This mechanism is responsible for the hydrolysis of some proteins by microwaves. The model predicts the dependence of the hydrolysis efficiency on
the relationship between the frequency of the electromagnetic field and the length of the polypeptide chain.

Enzymatic reaction in an external field

Zubkus and Stamenkovich in [94], Belousov, Kovarsky et al. in [195] considered changes in the rate of thermally activated enzymatic reactions in EMF at physiological temperatures. The influence
Microwave fields are reduced to a decrease in the activation energy of the reaction due to interaction of the electric component of the wave with the transition dipole moment along the reaction coordinate. Estimates of the effective amplitudes of the external field are not given, but the effective frequencies may correspond to the millimeter wave range.

Convection of cytoplasm and intercellular fluid

Monotonous increase in the intensity of Na+ ion transport through the skin
frogs with increasing power of mm radiation in the range of 0.1–
100 mW/cm2 Kazarinov, Sharov et al. [48] explained by the occurrence of convective currents of the aqueous medium near the surface of the skin.
This conclusion was confirmed by the absence of a frequency dependence of the effect when varying the wavelength range of continuous radiation.
ÿ(7.2–8.5/0.03)mm. Khizhnyak and Ziskin report that microconvective currents can be observed in aquatic systems already at a power
millimeter waves at 10 ÿW/cm2, [509].

Metastable changes in the properties of interstitial water

The topic of changes in the properties of the universal aquatic environment where biological processes occur under the influence of microwave radiation has been raised by many authors. Recently, some experimental confirmation has been obtained for this, see section 5.1. However, it is premature to claim that this explains that part of the biological
microwave effects, which reveals sharp resonances of action. To do this, it would be necessary to obtain the same resonant
responses separately on water samples, without connection with biological systems-moms.

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Local heating of the environment on a microscale

Lyashchenko [128] believes that the biological effects of MM waves can have an explanation in that the areas of water surrounding the Na, Cl, ions, K, etc., have different complex permittivity ÿ. Therefore, microwaves heat these ions differently. Something similar occurs at the membrane boundaries. The difference in ÿ is especially significant for ions of different hydration signs: (+) H, K, Rb, Cs, NO3, Br, J; (ÿ) Li, Na, Ca, Mg, SO4, CO3, Cu, Ni [76]. Local heating is associated with probable phase transitions, for example, in membrane structures [148], which causes a biological response. These processes do not have a strong frequency selectivity, which is necessary to explain the biological effects of the resonance type. Petrov and Betsky [159] believe that microwave radiation is capable of changing the conformation structure of the protein part of the ATPase complex. Known data are used that protein conformation depends on the amount water molecules bound to the protein by hydrogen bonds. At equilibrium the number of bound water molecules is determined by the rate of the thermally activated reaction

$$\text{protein}() + H_2O \rightleftharpoons \text{protein}(H_2O) .$$

On the other hand, the energy of the H2O molecule increases due to the absorption of a quantum hÿ of microwave radiation. The same change the energy of the molecule occurs when the temperature of the environment increases by hÿ/ÿ ÿ 2–3 K. Increasing the effective temperature governing the course of the binding reaction, is sufficient to influence the work of AT-Phase complexes.

In [227], Thompson, Young et al. suggested that frequency and power windows of biological response to microwave radiation could arise as a result of a phase transition in the system of abstract membrane EMF receptors associated with calcium-binding membrane proteins. In this model, however, the action of EMF on receptors, which should be of the order of energy ÿT and independent of frequency and power of the field, it is postulated. This circumstance leads to a model from a range of models suitable for solving the underlying problem magnetobiology.

Change in the concentration of dissolved gases

Dissolved gases are present in the intercellular plasma, part of the gas fraction forms microscopic bubbles. Yemets [84] showed,

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that when moving in a temperature gradient field, bubbles can grow. As a result, the concentration of dissolved gases decreases, which
leads to a cellular reaction. Suitable thermal gradients can be created by low-power microwave EMFs, from
0.3 mW/cm2. Such radiation does not change the temperature of the samples with an accuracy of 0.2 oC. Obviously, the temperature gradient caused by microwaves does not depend significantly on their frequency.

Quantum effects

The Davydov and Fröhlich models describe the quantum behavior of multiparticle systems. The biological effects of microwaves are also associated with
quantum transitions regardless of the microscopic device
systems. The general property of resonant quantum transitions is
narrowing of the resonant peak with decreasing radiation power, see,
for example, Fig. 4.19. The narrowing occurs until the natural
resonance width determined by the lifetime of quantum states.

Grundler and Kaiser [463] investigated the growth of yeast cells
under conditions of mm radiation in the region of 41.7 GHz with 8 kHz modulation at various power levels in the range from 10 mW/cm2 to
5·10ÿ6 ÿW/cm2. While the effect magnitude remained at 10–20%, a narrowing of the resonance peaks was observed with a decrease in the radiation power.

Belyaev, Shcheglov et al. [635] also observed a narrowing of the resonance peaks of bioeffects on E. coli cells. With attenuation of the 51.755 GHz radiation power from 100 to 10ÿ10 ÿW/cm2, the relative resonance width at half-height decreased monotonically from

ÿ2 10ÿ3 to ÿ 10ÿ4, in absolute units from 200 to 5–6 MHz. Reducing the power by another three orders of magnitude no longer led to a narrowing of the resonance. The effect/power dependence in this case had the form of a curve with saturation at 10ÿ11 ÿW/cm2 (the threshold varied depending on the density of the cell suspension), a form characteristic of the dependence of the probability of quantum transitions on the intensity of the resonant perturbation. It is not yet clear whether the recorded minimum width is related

resonance with the lifetime of quantum states in a biological system or with the radiation bandwidth of an MM wave generator: band
generator frequencies of ÿ 1 MHz coincided in order of magnitude with the observed resonance width. In [12], the resonance width on *E. coli* cells
also corresponded to the bandwidth of the generator, which was noted
authors. At the same time, the data [635] correspond to the idea of resonant quantum-

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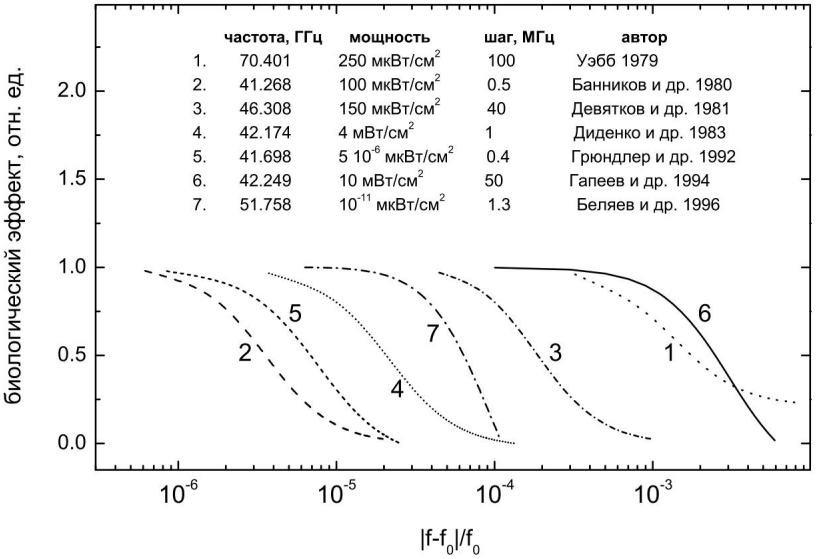


Fig. 5.7: Resonance widths of the biological action of mm waves: 1 – induction of prophage on *E. coli* cells [713], 2 – the same from [12], 3 – synthesis of penicillinase by staphylococcus [58], 4 – index of the Mössbauer spectrum hemoglobin [98], 5 – yeast growth [463], 6 – motility of unicellular organisms [168], 7 – state of the genome of *E. coli* cells [635].

transitions not only qualitatively, but also quantitatively, by a certain form of dependence of the resonance width on the radiation power.

From the formulas describing resonance in a two-level system, for example (4.67), it is easy to deduce that the resonance width at half-height, without taking into account natural line width, that is, at a sufficiently high power, is proportional to the square root of the pump power. A dependence close to this was observed in [635] with power attenuation from 100 to 10ÿ2 ÿW/cm2.

Figure 5.7 shows the contours of the Lorentzian approximation of several known results on the frequency spectra of the biological effects of microwaves. The data are presented in normalized form, in depending on the absolute value of the normalized deviation from resonance frequencies. It is clearly seen that the resonance widths correlate with the bandwidth of the generators' radiation, and not with the radiation power. Apparently, the observed resonance widths are not related to

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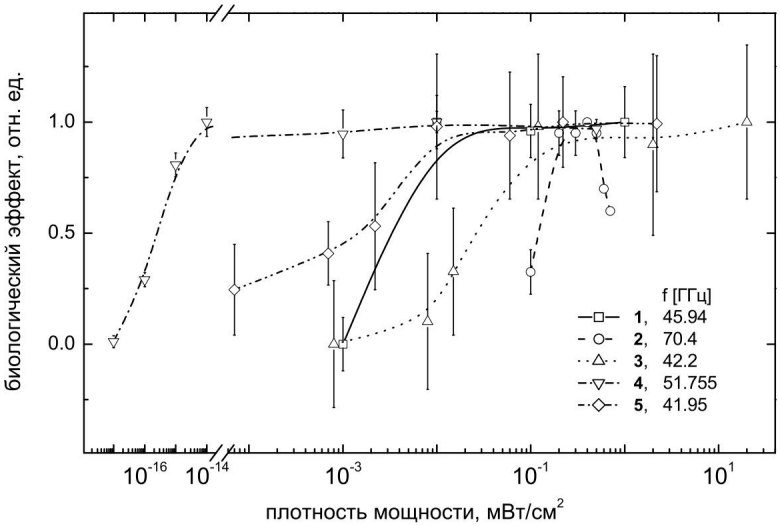


Fig. 5.8: Effects as a function of microwave power: 1 – synthesis cholecycin [169], 2 - induction of lambda prophage on *E. coli* cells [713], 3 — motility of unicellular *Paramecium caudatum* [168], 4 — conformational state of the genome of *E. coli AB1157* cells [635], 5 — inhibition of neutrophil chemiluminescence [138].

natural width of the "resonances" of the biological response.

Sometimes a relatively high threshold power is reported resonant biological effects of microwaves, of the order of fractions or units of mW/cm2 [58, 63, 168]. This could occur due to imprecise tuning to resonance. With a decrease in the radiation power, conditions arise when the radiation frequency no longer falls within the narrowed resonance peak. Figure 5.8 shows the known dependences of the resonant biological effects of microwaves on the radiation power, normalized to unity. It is evident that the assertion about the presence of a threshold power in the specified range is not sufficiently substantiated. There are works,
in which the threshold was observed in the region of 1 [138], 10ÿ2 [587], 5·10ÿ6 [463] and even in the region of 10ÿ12 ÿW/cm2 [635, 120]. In the latter case, the power of microwave radiation perceived by cells p was
5–6 orders of magnitude lower than the thermal radiation power level P. The latter can be easily estimated from the laws of blackbody radiation. Planck's formula for the radiation energy density per unit frequency

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interval

$$ÿ(ÿ)=8ÿh\left(\frac{ÿ}{c}\right)^{3}\frac{1}{\exp(hÿ/ÿT)\ ÿ\ 1}$$

in the case of frequencies in the gigahertz range at room temperature approximates the Rayleigh–Jeans radiation law well

$$ÿ(ÿ)=8ÿ\ ÿT\ .\ \frac{ÿ2}{c3}$$

Substituting ÿ ÿ 50 GHz and ÿ ÿ 5 MHz, we obtain the heat flux density radiation

$$P = ÿcÿ(ÿ)\ ÿ\ 10ÿ6\ ÿW/cm2\ .$$

This fact represents the same paradox as in low-frequency magnetobiology, the “kT problem.” Here it is especially good
It is clear that the “kT problem” is naturally divided into two equally important question, which was discussed in section 3.12. The first question is what is the mechanism for controlling a relatively powerful, ÿ ÿT chemical process using microwave field quanta hÿ ÿT . The second question is what is the mechanism for ensuring the stability of such control against the background of thermal disturbances with intensity P p.

■ Thus, there are sufficient grounds to believe that some biological effects of microwaves are due to quantum transitions at atomic levels. On the other hand, the idea is known

Arber, according to which the target of microwave radiation in living beings tissues are metalloproteins, in particular calcium-binding calmodulin [249]. Obviously, in the development of this hypothesis, one must assume, that microwave electromagnetic fields cause transitions in quantum states ion contained in the binding cavity of the protein.

Another important point is the remarkable analogy biological effects caused by microwave radiation and low-frequency magnetic fields, which has been noted by many researchers [527, 246, 322, 306, 675]. The amplitudes of these effects in the same biological systems are close in magnitude. Both require the fulfillment of certain conditions. In particular, time

the constancy of radiation parameters must exceed a certain threshold [534, 639]. Both of them disappear when an additional low-frequency fluctuating MF is superimposed [306]. Close ones turn out to be frequency spectra of action of low-frequency MF and modulated MM radiation (dependence on modulation frequency) [640, 693].

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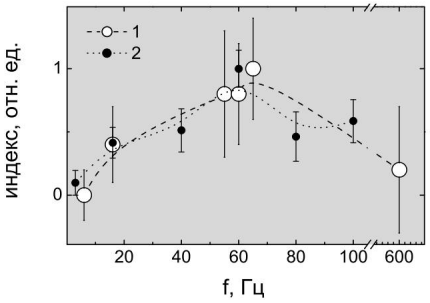


Fig. 5.9: Dependence on microwave modulation frequency: 1 – ornithine decarboxylase activity in L929 cells [640], 2 – inhibition of T-lymphocyte cytotoxicity [686].

Thus, Bowen, Kaczmarek and Edie in [268] investigated the rate of 45Ca2+ ion leakage from chicken brain tissue when irradiated with amplitude modulated radiation with a frequency of 147 MHz at a modulation frequency of 0.5–35 Hz. The increase in speed reached a maximum of 20% at frequency of 16 Hz, Fig. 5.10.

The influence of microwaves with a power of ÿ 1 mW/cm2 and a frequency of 835 MHz on Ornithine decarboxylase activity in L929 cells was studied by Penafil, Litovitz et al. in [640] with different types of modulation. The greatest changes, ÿ90%, occurred with amplitude modulation with frequencies of 16 and 60 Hz after 8 hours of exposure and dropped to the control level after 24 hours of exposure. Other types of modulation, frequency, pulse, speech, etc., turned out to be significantly less or not at all

ineffective. The efficiency spectrum of modulation frequencies at modulation depth m = 0.23 and exposure time of 8 hours is shown in Fig. 5.9. The presence of an extremum is visible; the range of effective modulation frequencies corresponds to the frequency range of low-frequency magnetic fields that cause a similar biological effect in the same cell culture.

[693] The influence of amplitude-modulated 450 MHz microwaves on the The same biological system with an effect of up to 60% was studied in [481].

Lyle, Schechter et al. [686] report that amplitude modulated 450 MHz radiation 1.5 mW/cm2 inhibits T-lymphocyte toxicity in relation to cancer cells. Dependence on the modulation frequency had an extremum at a frequency of 60 Hz, Fig. 5.9. At the same frequency, the maximum inhibition effect was observed during exposure to low-frequency EF [687].

Grigoriev and Stepanov [461] found that modulated 10 GHz radiation with a power of 40 ÿW/cm2 causes suppression of imprinting4 in

4Imprinting is the ability of animals to remember at the initial stage of development. distinctive features of the external stimuli acting on them.

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chick embryos after just five minutes of exposure. The effect was observed at modulation frequencies of 9–10 Hz and was not observed at frequencies of 1–3
40 Hz.

Kuznetsov, Golant, and Bozhanova [120] used pulse-modulated microwave radiation in experiments on synchronization of cell cycles by radiation. A modulation frequency of about 10 Hz provided the maximum effect.

The level of the local constant magnetic field and its orientation with respect to the microwave field configuration in all these experiments
did not control.

■ The observed similarity between the biological effects of microwaves and low-frequency magnetic fields indicates a possible common nature of the physical processes underlying these effects. Since a number of low-frequency magnetic field effects can be successfully explained within the framework of the ion interference mechanism, it makes sense to also consider its features under microwave field conditions. The purpose of such consideration is the theoretical derivation of the dependencies of the dissociation probability of complexes.
ion-protein interaction with the microwave amplitude modulation frequency. Such dependences are quite simple to measure experimentally—there is no need to change the carrier frequency, which is usually associated with the probable occurrence of artifacts [508, 138]—therefore, there is a convenient opportunity for experimental verification of the theory's predictions.
Let us also note that the natural frequencies of quantum transitions of particles with the parameters of Ca, Mg, etc. ions in the effective potential of radius R ÿ 0.7 A
°, which corresponds to the binding cavity of calmodulin,
exactly correspond to the millimeter range of wavelengths of EM radiation, see section 4.1. Moreover, as already mentioned, in the experiment a number of close spectral maxima are often observed, spaced
from each other by 10–50 MHz. This also fits into the concept of
quantum levels sequentially excited during scanning
frequencies. This splitting probably occurs due to the additional potential of octahedral symmetry, which perturbs the idealized spherical potential of the protein ion cavity.

5.2.3 Interference in microwave EMF with modulation

Interaction of a simple quantum system with a plane EM wave
We don't consider this here. The specifics of such interaction are well
are known, see, for example, [70]. We will limit ourselves to the study of interference

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dissociation effects caused by amplitude modulation
carrier wave.

The state of an ion in a cavity is determined by the superposition of its basis states |k

$$ÿ(r, ÿ, ÿ)= \sum_{k} ck(t)|k .$$

Here we assume that all states |k of the ion are renumbered in a row, without specifying the radial, azimuthal, and magnetic quantum numbers. The density matrix in this representation has the form

$$ÿnk = cÿ nck .$$

It obeys the quantum Liouville equation, in which the perturbation is associated with broadband amplitude-modulated EM radiation. Within the framework of this preamble, the derivation of the equation exactly repeats the procedure outlined in the first half of Section 3.8.2, devoted to parametric resonance in a three-level atomic system. Therefore, we retain the notation and approximations adopted in

in that section and start immediately with equation 3.44 for the cross terms density matrices responsible for interference effects

$$ÿÿ_{nk} = ÿ (ÿnk + iÿnk) ÿnk + Fnk .$$

Let us remember that here ÿnk are the attenuation coefficients, ÿnk are the frequency gaps in the Zeeman sublevels, and the pump matrix

$$Fnk ÿ vÿ \frac{2ÿE^2ÿ_{00}}{\hbar^2}$$

includes the spectral density E of the electrical component of the EMF, which was assumed to be constant in time and independent of frequency, that is, E = Eÿ = Const. This is based on the fact that the bandwidth of microwave radiation is much larger than the Zeeman splitting, even in very sophisticated generators.

In contrast to the case of modulation of the Zeeman gap width in an alternating low-frequency magnetic field considered in section 3.8.2, here
Let's consider the modulation of the microwave carrier intensity. This leads to the pump matrix becoming a function
time. Since the pump matrix is proportional to the square of the spectral density, it is simply expressed in terms of the pump matrix
Fnk in the absence of modulation, [7]:

$$Fnk()= Fnk (1 + \cos ÿt) ,$$

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where ÿ is the frequency and is the modulation depth. The equation for crosstalk members of the density matrix takes the form

$$ÿÿ = ÿ (ÿ + iÿ) ÿ + F(1 + \cos ÿt) ,$$

and there is a solution

$$ÿ = eft C + eÿftg dt ,f ÿÿÿ ÿ iÿ , g(t) ÿ F(1 + \cos ÿt) .$$

Here, for convenience, the indices n and k are temporarily omitted. Let us set the initial conditions such that C = Const = 0

$$ÿ = eft eÿftg dt .$$

Having found the integral, we obtain

$$ÿ = F \quad \frac{1}{ÿ+ iÿ} + \frac{}{2}\frac{\exp(iÿt)}{ÿ+ i(ÿ + ÿ)} + \frac{}{2}\frac{\exp(ÿiÿt)}{ÿ+ i(ÿ ÿ ÿ)} \quad . \qquad (5.5)$$

Change in intensity of re-radiated EM field upon coincidence
the modulation frequency and the frequency of the difference (Zeeman) levels, determined by the elements of the density matrix (5.5), is known as “resonance beats" [7]. In contrast, we are interested in changes in the internal density distribution of the particle, which affects the probability
its exit from the linking site.

Let us write down the wave function of the ion within the framework of those approximations and with the-
with the same designations that were already used in Section 4.1

$$ÿ= \sum_{kmm} dklmRklP \; {}^{m}_{l} ÿm .$$

The coefficients dklm, unlike 4.5, depend on time due to
microwave-induced transitions. Let us now write down the probability density of an ion at a certain angular position

$$\begin{aligned} p(t, ÿ0)&= \\ &= ÿ(t, ÿ0)|ÿ(t, ÿ0)r,ÿ = \\ &= \sum_{kk\,llmm} dÿ\; klmdk\; lm\; Rk|Rk\; P \; {}^{m}_{l}|P\; m\; l\; ÿm(ÿ0)\; ÿÿm\; (ÿ0)= \\ &= \sum_{mm} ÿmmamm \quad eÿi(mÿm\,)ÿ0 \quad , \end{aligned} \qquad (5.6)$$

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$$\ddot{y}mmamm\ \ddot{y} \qquad d\ddot{y}\ klmdk\ lm\ Rk|Rk\ P \qquad {}^{m}_{l\ |P\ m\ l} \ .$$

kk ll

Here the coefficients amm , which determine the initial conditions, are clearly extracted from the density matrix ÿ. Let us now substitute the found density matrix (5.5) into the expression for the probability density (5.6). When In this case, we take into account that the first, constant term in (5.5) is not of interest to us. The phenomenological attenuation coefficients in the density matrix make sense in connection with the previously introduced value of the lifetime of magnetic modes. We assume that they are all the same and equal to ÿmm = ÿ=1/T . Let us also omit the constant factor 1/2, which is not essential for what follows. Taking into account all that has been said, returning the indices to the expression (5.5), we write the probability density in the following form

$$p = \sum_{mm} amm \left(\frac{F \exp(i\ddot{y}t)}{\ddot{y} + i(\ddot{y}mm + \ddot{y})} + \frac{F \exp(\ddot{y}i\ddot{y}t)}{\ddot{y} + i(\ddot{y}mm\ \ddot{y}\ \ddot{y})} \right) \exp(im\ddot{y}0) \ .$$

For the Zeeman multiplet ÿmm = ÿ0m. We denote

$$\ddot{y}+ = \ddot{y}0m + \ddot{y} \ , \ddot{y}\ddot{y} = \ddot{y}0m\ \ddot{y}\ \ddot{y} \ .$$

The probability density takes the form

$$p(t, \ddot{y}0) = F \sum_{mm} amm \left(\frac{\exp(i\ddot{y}t)}{\ddot{y}+ i\ddot{y}+} + \frac{\exp(\ddot{y}i\ddot{y}t)}{\ddot{y}+ i\ddot{y}\ddot{y}} \right) \exp(im\ddot{y}0) \ . \quad (5.7)$$

Unlike (4.8), the probability density (5.7) oscillates with a single frequency ÿ. Therefore, in this case there is no need to isolate the slow components of the oscillations by performing a moving average over time.

In the sum (5.7) there are complex conjugate terms, namely m, m, and m m. When multiplied and averaged, they create a nonzero contribution. Let's write out a pair of such terms:

$$amm \left(\frac{\exp(i\ddot{y}t)}{\ddot{y}+ i\ddot{y}+} + \frac{\exp(\ddot{y}i\ddot{y}t)}{\ddot{y}+ i\ddot{y}\ddot{y}} \right) \exp(im\ddot{y}0)$$

$$amm \left(\frac{\exp(\ddot{y}i\ddot{y}t)}{\ddot{y}\ \ddot{y}\ i\ddot{y}+} + \frac{\exp(i\ddot{y}t)}{\ddot{y}\ \ddot{y}\ i\ddot{y}\ddot{y}} \right) \exp(\ddot{y}im\ddot{y}0) \ .$$

All products of other pairs that do not form a permutation

$m\ \ddot{y}\ m$, will disappear due to averaging over an arbitrary angle ÿ0.

Thus, the square of the density p(t, ÿ0) will consist of the sum

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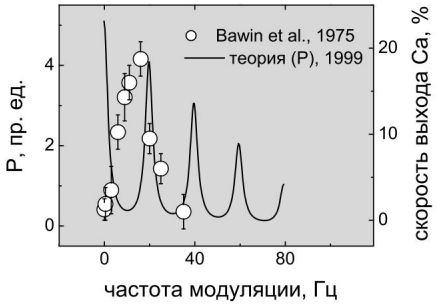


Fig. 5.10: Experimental data [268] after 45Ca2+ from brain tissue and theoretical calculation for these ions in field HDC = 50 ÿT, ÿ=ÿcT = 20.

products of the terms written out. We multiply them, simultaneously averaging over time, that is, discarding the terms containing exponents dependent on t. Where from

$$\overline{P \ddot{y} p2(t, \ddot{y}0)} = F2\,2 \sum_{mm} |amm|^2 \left(\frac{1}{\ddot{y}2 + \ddot{y}2_{+}} + \frac{1}{\ddot{y}2 + \ddot{y}2_{-}} \right) .$$

Since we are studying the case ÿ ÿ ÿ, that is, when ÿÿ ÿ 0, ÿ+ ÿ 2ÿ, then one of the two members makes only a small adjustment to the results. Therefore, it is omitted below. The final formula for the dependent on the fields of the dissociation probability part are as follows

$$P = \sum_{mm} |amm|^2 \frac{F22}{T\,\ddot{y}2 + (\ddot{y}0m \ddot{y} \ddot{y})2} , \qquad (5.8)$$

or in dimensionless variables, accurate to a coefficient

$$P = \sum_{mm} |amm|^2 \frac{2}{1 + [(m/2 \ddot{y} f)\ddot{y}]2 .} \qquad (5.9)$$

The quadratic dependence of the effect on the modulation depth is noteworthy. However, due to the general nonlinear nature of the biological response to an increasing stimulus, experimental verification of this dependence is difficult.

The frequencies of the effect maxima are the same as in the case low-frequency MP, series

$$f = m/2 . \qquad (5.10)$$

The difference is that now f = ÿ/ÿc is the relative modulation frequency of microwave radiation. Thus, *if the biological effect of amplitude-modulated microwave*

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radiation is a consequence of the interference of ionic states, then the dependence on the modulation frequency has maxima,
and the frequencies of the maxima are directly proportional to the local constant MF. This position [299] can be verified experimentally.

Figure 5.10 shows experimental data [268] that have not yet been interpreted in the scientific literature.
The calculation within the framework of the interference mechanism is also shown. Since constant MP was not recorded during the experiment,
For the calculation, the probable value of the magnetic field HDC = 50 ÿT was chosen. The remaining parameters are the same as in other calculations for calcium. It is visible qualitative agreement between experiment and theory.

Interference in a microwave field without modulation

The described mechanism does not predict effects in the absence of MM signal modulation, at = 0. This is obviously inconsistent
with numerous observations of the biological effects of unmodulated microwaves. We will present here without any calculations the statement that,
that within the framework of the ion interference mechanism such effects can originate from rotating ion-protein complexes. As shown in Section 4.5, rotation of complexes in a constant magnetic field
lead to effects similar to the action of variable MPs against the background constant field. Only those rotations of the complexes that are coordinated in speed with the magnetic field level lead to the observed effects.
On the other hand, in the case of microwaves, it must be considered that the role of the modulating factor is taken on by the proper rotations of the ion-protein complexes. If this is true, then *the resonance peaks of the biological action of unmodulated microwaves disappear during macroscopic rotation of the biological system. A change in the level of constant magnetic field leads to the disappearance of the previously observed*
resonance peaks and the emergence of new peaks at other frequencies. It is precisely this behavior of the microwave frequency spectra of the bioeffect with a change in the level of a constant magnetic field that Fesenko and coworkers observed in their work [675]. The activity of mouse neutrophils was measured by the chemiluminescence of the probe in response to continuous radiation.
50 ÿW/cm2. When the local magnetic field changed from 50 to 100 ÿT, both the sign of the effect at an absolute level of about 25% and the position of the spectral maximum changed from 41.95 to 42.00 GHz.

There are experimental data [168] on the dependence of the biological effect on the frequency of microwave modulation by a meander of 0.091–
0.102 Hz, which is an order of magnitude lower than the relevant ion frequencies. It is likely

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but, at the primary level, the effects of continuous microwave radiation occurred, but for their manifestation at the biological level
it was necessary to get into resonance with some internal rhythms
with a period of about 1 s, for example, as the authors note, with fluctuations in the concentration of intracellular calcium. Complex dependences of the effect on the frequency of the carrier signal and on the modulation frequency, including
with a change in the sign of the effect was observed in [139]. However, even in this case The characteristic modulation frequencies were quite low, around 1 Hz. This
justifies the authors' conclusion that microwave reception involves a system of related biochemical reactions with characteristic frequencies in this range. At the same time, the primary reception itself
can occur regardless of the presence of modulation. Thus,
the effect of microwaves on biological systems, like the effect of low-frequency magnetic fields, can be of a hidden nature and, therefore, lead, like chemical agents, to unpredictable remote effects
consequences.

5.2.4 Dissociation in the field of a wave with circular polarization

Let us now consider the features of dissociation in the field of circularly polarized radiation. Let us consider the changes that need to be made in
derivation of the equation for the cross elements of the density matrix, presented in Section 3.8.2. We will show that, in comparison with the case
plane-polarized radiation, the changes will only affect the matrix
pumping.

Let ex, ey, ez be the unit vectors of the Cartesian system. A plane-polarized wave, for example in the y = 0 plane, propagating along
the z-axis can be written as

$$Ex = ex \cos ÿt = \frac{1}{2} ex\, eiÿt + eÿiÿt \quad , \qquad (5.11)$$

where the intensity of the wave $\overline{EE}$ is taken to be equal to unity, and in the expression for the wave phase ÿtÿkz, the term kz, which is not essential in this section and describes the change in phase in space, is omitted. Circularly
a polarized wave whose vector end forms in space
right or left screw, is a superposition of two coherent plane-polarized waves in different planes with a certain pha-

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a key shift. For example,

$$E+ = ÿ2 \frac{1}{=} (ex \cos ÿt ÿ ey \sin ÿt)$$

$$Eÿ = \frac{1}{=} (ex \cos ÿt + ey \sinÿt) , ÿ2$$

where the wave is again normalized to unit intensity. Such waves are conveniently written in a different, special basis. For this purpose, so-called cyclic unit vectors are introduced.

$$e+ = ÿ \quad \frac{1}{=}(ex + iey) , ÿ 2 \quad eÿ = \quad \frac{1}{=}(ex ÿ iey) , ÿ2 \quad e0 = ez .$$

Then for a circularly polarized wave one can use a notation formally close to (5.11)

$$E± = ÿ 2 \frac{1}{-} e±eiÿt ÿ eÿeÿiÿt . \qquad (5.12)$$

When deriving the equation for the density matrix in Section 3.8.2, the perturbation operator of the atomic system included a linearly polarized field of broadband radiation (3.35). Comparing expressions (5.11) and (5.12), we find that circularly polarized radiation,5 for example,
E+, should be written as

$$E+(t)= eÿ Eÿ \exp (ÿiÿt ÿ iÿÿ) dÿ ÿ e+ Eÿ \exp (iÿt + iÿÿ) dÿ .$$

The difference from the case of plane-polarized waves essentially consists only in the fact that the complex conjugate terms in (3.35) now have different polarizations. Further in the derivation of the density matrix equation, only one of these terms is used, since the other is associated with the emergence of rapidly oscillating terms, the contribution of which can be neglected. Therefore, the matrix elements v0k from (3.39), which are included in the pump matrix (3.43), should be written as follows:

$$v0k = 0|deÿ|k .$$

In [7] (Chapter 4) it is shown that the matrix elements of the dipole moment operator in a cyclic basis have the form

$$n|d|k = eÿdkn \quad ,$$

The emission spectrum width must cover the Zeeman splitting but be much smaller than the carrier frequency. These conditions are well satisfied in the experiments discussed here.

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where dkn are coefficients depending on the quantum numbers of states
n, k, and ÿ = mk ÿ mn is the difference in projections of the total magnetic moment
on the quantization axis. Then, since the unit vectors e do not affect the wave functions
and can be taken outside the quantum brackets, the matrix elements v0k
equal

$$v0k = dk0eÿ\ eÿ\ .$$

These elements are included in the pump matrix in combinations vÿ 0nv0k. Therefore,
without loss of generality, taking into account the possibility of circular polarization of radiation
is reduced to replacing the pump matrix in the equation for
density matrices

$$Fnk ÿ\ Fnk|eÿeÿ|^{2}\ .$$

Obviously, due to the properties of the scalar product of vectors, the pumping
is maximum at eÿ = e+ and is zero at eÿ = eÿ. These selection rules, dictating the
conservation of the sum of the projection of the total moment of the atomic
the system and the photon in the dipole transition determine which of the polarizations of
external radiation, right or left, will be effective.
If the dissociation of the atomic-like system discussed in section
5.2.3, is associated with a dipole transition from the ground to the excited state with a total
momentum differing by one, then the probability
dissociation (5.8) will be non-zero for microwaves only,
right or left, circular polarization. Linearly polarized
radiation that is a coherent superposition of circular
waves of opposite polarization are also effective. The power of one circular component is
equal to half the power of linearly polarized radiation. However, since the pump matrix is
directly
proportional to the radiation power, is included in the expression for the probability
dissociation probabilities in the form of a square F2, then linearly polarized
the radiation will create a four times smaller dissociation effect,
than circularly polarized radiation of equal power.

A similar dependence of the biological effects of MM radiation
of varying power depending on the state of its polarization were observed in the cycle
experiments, a review of which is given in the work of Belyaev, Shcheglov, and others.
[589] For example, in the range of 41.25–41.50 GHz, which corresponded to the spectral
maximum of the effect, microwaves of 10–200 ÿW/cm2
left polarization, close to circular, had statistically significant effects
a significant 10–20% effect on *E. coli* cells pre-irradiated with X-rays. Right-handed
polarized microwaves were
ineffective, and linearly polarized microwaves produced an effect of intermediate
magnitude. In another spectral maximum, on

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At a frequency of 51.76–51.78 GHz, on the contrary, the effect was observed only for right-hand polarization. The conclusion was that biological reception microwaves involve quantum transitions with selection rules according to helicity.

Note that with decreasing microwave intensity, the semiclassical approximation—the approximation in which a quantum atomic system interacts with classical EM radiation—generally speaking, becomes inapplicable. However, in this particular case, the conclusions boil down primarily to the statement of the law of conservation of angular momentum, which is valid regardless of the chosen level of description, semiclassical formalism or quantum electrodynamics. Therefore, the conclusions of this section are equally applicable in the region of ultra-low microwave radiation powers, where biological effects also observed, see Fig. 3.1. In this case, the concept of helicity of quanta of EM radiation becomes an adequate characteristic of the radiation — quantum number (±1) characterizing the projection of the photon spin onto the direction of its momentum vector.

5.3 General ideas in electromagnetic biology

There are several scientific fields indirectly related to electromagnetic biology. They examine quantum processes. interactions between EMFs and the structures of biological tissues. Therefore, it is important to identify common points that indicate a possible physical the nature of molecular targets and mechanisms of biological action EMP.

5.3.1 Electret states

Del-Giudice, Doglia et al., see, for example, [367, 681], are developing quantum field description of biological matter, or more precisely, its polarization. The Lagrangian describing the polarization field of the medium is invariant with respect to transformations of the continuous group of rotations, — due to the assumed initial isotropy of the medium. However, the ground state of the medium, which is the solution of dynamic Lagrangian equations, may not have the symmetry of the Hamiltonian and may have reduced symmetry due to the emergence of a state with spontaneous polarization, the electret state. It is believed that biological tissue containing a large number of molecules with

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dipole moment, can be, at physiological temperature, in *different sets* of states with non-zero macroscopic polarization P. The latter plays the role of an order parameter for
electret states. Each set is defined in its own state space in accordance with the value of the parameter P and is characterized by its own dynamics or Lagrangian. Transitions between sets of states are determined by interactions with the external environment.
Thus, a “two-dimensional” dynamics arises: the system evolves within each of the state spaces in accordance with
a certain Lagrangian dynamics and experiences transitions between different spaces under the influence of external factors, such as heat or metabolic energy. This behavior leads to correlation in the oscillations of individual dipoles and manifests itself as waves
macroscopic polarization, - dipole waves. In this scenario
Fröhlich coherent excitations are observed, justified
within the framework of the quantum field approach.

In the complementary description, dipole waves correspond to massless particles—quanta with Bose-Einstein statistics. Ordering or coherence in the system arises as a consequence of Bose condensation of particles in the ground state. Since these bosons
do not have mass, then maintaining a coherent state does not require additional energy input from the outside. Vitiello [706] sees in
this is the basis for explaining one of the mysteries of biology - conservation of the organism as such, that is, maintaining macroscopic coherence, under conditions when the external energy source does not contain
information about any order.

External EMF changes the nature of polarization waves in the medium, such a medium is nonlinear with respect to EMF. Specific
The interaction of external electromagnetic fields with polarization waves, or dipole modes, has an important consequence. The propagation of electromagnetic waves in such a medium it is no longer described by the d'Alembert wave equation, following from Maxwell's equations

$$A\ddot{y} = j\ddot{y}, \qquad \ddot{y} \frac{\ddot{y}2}{\ddot{y}x\ddot{y}\ddot{y}x\ddot{y}},$$

where Aÿ is the 4-EMF potential, jÿ is the 4-vector of current density. Dynamics EMF in the environment obeys the equations

$$A\ddot{y} + M2A\ddot{y} = j\ddot{y}, M2\ \ddot{y}\ P, \tag{5.13}$$

which entails a number of consequences that are important for the interpretation of general

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biological patterns. For example, the electromagnetic field propagating according to equations (5.13) is limited to regions similar to sufficiently thin threads, so that large gradients arise at the edges
EMF. Separation and concentration occur on field gradients.
various ions, molecules and molecular groups. Therefore, the filiform the propagation of EMF in a medium with spontaneous polarization becomes "structure-forming" morphological factor and is capable of explaining, for example, the emergence of such structures as microtubules
cytoskeleton ki.

The Del Giudice et al. model may be indirectly related to magnetobiology. In [681] it is suggested that liquid water is a dipole medium in which polarization waves arise. We add that the low-frequency magnetic field, acting on the spin magnetic moments
The magnetic field, which regulates proton mobility to some extent, influences the probabilities of various orientations of water molecules. Thus, the magnetic field could influence the properties of polarization waves, causing the final biological effect.

5.3.2 Raman scattering on organisms and the effect tymm waves

In quantum theory, Raman scattering of light is considered a two-stage process. In the first stage, the quantum system absorbs a photon with energy ÿ and goes into
virtual state, on the second one it emits a photon with energy ÿ and returns to the ground or excited state. The energy of the scattered photon may remain unchanged, ÿ = ÿ, in which case we speak of Rayleigh scattering. The photon may give up part of its energy to the quantum system, and then a line shifted to lower frequencies, ÿ = ÿ ÿ ÿ, appears in the scattering spectrum—this is
Stokes scattering. Conversely, if a photon, when scattered, carries with it part of the energy of the quantum system, this is anti-Stokes scattering.
The diagram of processes in a quantum system during scattering of electromagnetic radiation, the emergence of Rayleigh, Stokes and anti-Stokes lines in the scattering spectrum, are shown in Fig. 5.11. As a result of Stokes or anti-Stokes scattering, the quantum system experiences
transition to another state. In a Stokes process, the system transitions from the ground to the excited state, in the anti-Stokes, on the contrary, from excited to the ground state. Since, under conditions of thermal equilibrium, the populations of the excited and ground states are related as

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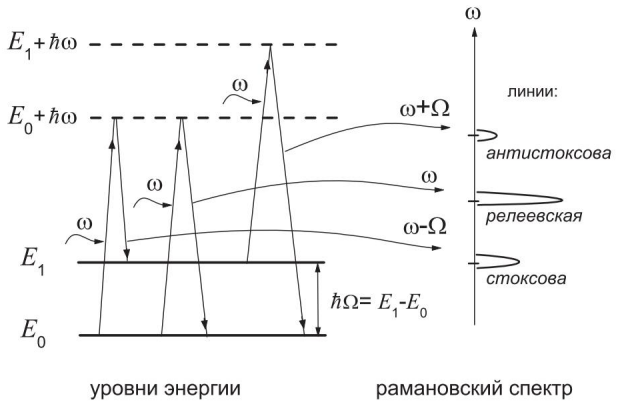


Fig. 5.11: Quantum transitions in Raman scattering of electromagnetic radiation and the Raman spectrum, including the Rayleigh, Stokes and anti-Stokes lines.

n1/n0 = exp [ÿÿ/ÿT], the intensities of the Stokes and anti-Stokes lines are generally not the same. If the splitting E = ÿ is much
less than the thermal scale ÿT , then the levels are equally populated and intensive the Raman lines are equal.6 Otherwise, as is usual
It happens with the electron terms of molecules, the anti-Stokes component is much weaker than the Stokes one.

Often a quantum system is characterized by multiple levels of that
or another structure. Then, in the spectrum of scattered light,
Multiple lines corresponding to transitions in these levels—Raman transitions. The positions and intensities of these lines carry information about the structure and state of the quantum system. Therefore, Raman scattering is a powerful tool for studying molecular, including macromolecular, processes *in vitro.*

A series of studies on the features of Raman scattering on biological cells *in vivo* in various metabolic states
conducted by Webb, Stoneham, and others since 1971. The results of this work are covered in the review by Webb [714]. The cells studied were *B. megaterium, E. coli,*
mammalian carcinomas. In the frequency range 0–3400 cmÿ1 7 about-

6Since the radiation intensity is ÿ ÿ4, then, more precisely, the ratio of intensities is equal to Ias/Ist = exp [ÿÿ/ÿT](ÿ + ÿ)4/(ÿ ÿ ÿ)4, away from the frequencies ÿ of the resonant dis-sowing.

7 cmÿ1 is the spectroscopic unit of frequency, equal to 30 GHz (from the relation f /c = ÿÿ1).

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many Raman lines have been discovered that appear only
when the cells are in a metabolically active state. Raman spectra (positions and intensities of lines) change according to
as the cell goes through its development cycle. The spectra are reproducible in essential features in different cell culture samples. Several dozen lines with frequencies greater than 300 cmÿ1 are shifted
into the high-frequency region, with frequencies less than 300 cmÿ1 (about ten lines) - towards the Rayleigh line. A strong scattering line on
E. coli cells moved for an hour at an average speed of 0.5 cmÿ1
per minute from 158 cmÿ1 to 126 cmÿ1. Some lines periodically disappeared and reappeared during the cellular
cycle. Thus, Raman spectra on *in vivo* systems provide information about cellular metabolic processes, reflect
physiological state of the cell.

Raman scattering with similar properties was also discovered by other authors: on the cells of the seaweed *Clorella pyrenoidosa*
Driessler and McFarlane, see [375], on *B. megaterium* cells
Bannikov, Bezruchko and others [97].

The energy ÿT corresponds to a frequency ÿT/2ÿc of approximately 230 cmÿ1. Therefore, as stated above, under thermal equilibrium conditions, anti-Stokes lines with frequencies significantly greater than 230 cmÿ1 should be significantly weaker in intensity than their Stokes pairs, and those with frequencies greater than 500 cmÿ1 should not be visible. However, this is not always the case.
Scattering by algal cells [375] shows strong anti-Stokes lines in this range. Moreover, anti-Stokes lines near
1000 cmÿ1 are stronger than their Stokes companions. In the region below 200 cmÿ1
There are also some peculiarities. For lines in the range of 100–200 cmÿ1 at physiological temperature equilibrium ratio of intensities
anti-Stokes/Stokes should be in the range of 0.65–0.42. At the same time, Webb's data [714] show that the line pair at about ±130 cmÿ1 on E. coli cells had almost equal heights. The excited level population, calculated from Driessler's data [375] for the relative intensity of the ±868 cmÿ1 lines, exceeded the thermal population by a factor of 2.6. From the discrepancy between the expected and measured relative heights of the Raman satellites, it follows that the excitations on
which scattering occurs, are not thermalized, that is, they disintegrate,
without having time to reach thermal equilibrium with the environment after their emergence. Or the statistics of such excitations are not Boltzmann at all.

There is a quantum effect that regulates the differences in intensity.

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Raman scattering satellites. Let the number of excitation quanta of excited level 1 in Fig. 5.11 in the representation of numbers
The filling number is n, and the main number is m. It is clear that the Stokes process increases the number n by one and decreases the number of quanta m by one.
This can be represented as the action of the creation operator a+ on |n and annihilation operator b on |m. The result is the emergence of
from |n, m state |n +1,m ÿ 1. According to the rules of normalization of wave functions of this representation

$$a+b\,|n, m = ÿ\, n +1ÿm\, |n +1,m ÿ 1 .$$

The intensity of the process is proportional to the square of the corresponding matrix element, that is, (n + 1)m. The second part of the perturbation operator a+b+b+a, which causes transitions in the indicated levels, obviously, on the contrary, decreases the number n by one and increases by one
m, and describes the anti-Stokes process:

$$b+a\,|n, m = ÿn\, ÿm +1\, |n ÿ 1,m +1 .$$

The intensity of this process is n(m + 1). Thus, if
thermal and, perhaps, metabolic processes maintain the populations of states at the level of n and m quanta, respectively, the intensity ratio Ias/Ist = n(m + 1)/m(n + 1). Ground state
usually populated so that m 1, therefore

$$\frac{Ias}{Ist} = \frac{n}{n +1} .$$

If, judging by the Boltzmann statistics, n = 0 with a high probability, but from the experiment it follows that Ias/Ist ÿ 1, then this indicates
deviation of excitation statistics from the Boltzmann one. Indeed, collective vibrational modes are bosons and obey the Bose-Einstein distribution

$$nk = e(Ekÿÿ)/ÿT ÿ 1^{-1}, \qquad (5.14)$$

where nk is the average number of excitation quanta (or particles) in the k-th mode with energy Ek, ÿ(T) ÿ 0 is the chemical potential such that ÿ ÿ 0 when
T ÿT0, T0 is the degeneration temperature. At T0 T the average number
particles in the k-th mode

$$nk ÿ \exp (ÿ ÿ Ek)/ÿT$$

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obeys Boltzmann statistics. However, if T < T0, then only
some of the particles are distributed according to formula (5.14). The other part, proportional to 1 ÿ (T /T0)2/3, is in a state with Ek =0, that is, experiences Bose-Einstein condensation.

Levels 0 and 1 in Fig. 5.11 are not, in general, levels of any one specific quantum number. It is believed that
level 1 may be the main one in some series of nk levels of collective excitations. If the number of excitation quanta of this level is large, then Ias/Ist = 1. Fröhlich [442], Wu [724, 725] and many other researchers interpret the equality of the intensities of the Stokes and anti-Stokes lines near 130 cmÿ1 in scattering on *E. coli,* see [714], and in general the anomalies of Raman scattering on metabolizing cells,
- as evidence of Bose condensation caused by metabolic processes and a sharp increase in the number of excitation quanta of lower vibrational modes.

There are different points of view on the nature of those quantum excitations in a living system that are responsible for the appearance of Raman scattering lines. Scott [654] analyzed Webb's data on
Raman lines in the range of 45–182 cmÿ1, excited by laser radiation of 5145 A°, on E. coli cells. He pointed out that
the series of these lines is close to the series of combination frequencies formed from the frequencies of internal vibrations of the Davydov soliton calculated by him, 17 cmÿ1 and 125 cmÿ1, see Appendix 6.6. Since, as shown
Kruskal and Zabusky [731] noted that solitons often behave like particles, retain their individuality, that is, their form in the processes of collision with each other, then it makes sense to consider them as quanta of excitations and in the processes of interaction with excitations of a different nature, phonons and photons. According to Scott, the origin of low-frequency lines Raman scattering on metabolizing cells is associated with scattering on Davydov solitons. The shift of these lines to the low-frequency region during the cell life cycle reflects a decrease
the rate of propagation of solitons with cell aging.

From the point of view of electromagnetobiology, the Raman lines in the range of 1–3 cmÿ1 (30–90 GHz) would be of greatest interest ,
- lines possibly associated with excitations responsible for
biological effects of microwaves. However, the resolution of Raman
The range of laser-excited spectrometers, typically 2–5 cmÿ1, is insufficient for reliable recording of such spectra. In addition, with laser excitation, the specified range is covered by the intense wing of the Rayleigh line. Probing excitations of the specified range

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zone was achieved by exposing objects to a microwave field and measurements of re-radiated waves at a significantly lower frequency region, - the decimeter range. In essence, we are talking about spontaneous luminescence in the radio wave range.

5.3.3 Radio wave luminescence of water and organ- mov

Luminescence is an excess of radiation compared to thermal radiation, lasting longer than the period of the emitted wave. Usually, the emitting centers are atoms and molecules, which determines the range of radiation spectra from optical to infrared. At the same time, nothing prevents certain collective atomic-molecular excitations from being a source of characteristic radiation, which in this case should be of significantly lower frequency. Petrosyan, Gulyaev et al. [38] discovered that when various liquid media and entire biological objects are irradiated with microwaves, they themselves begin to emit electromagnetic waves in the decimeter range above

thermal level. The object's response to microwave exposure was detected using a microwave radiometer at a frequency of 0.4 or 1 GHz in a frequency band of 50 MHz. The radiometer's sensitivity was 0.3 K, time constant ÿ1 s. The luminescence excitation spectra were measured by scanning the excitation frequency in the range of 4–120 GHz. It turned out that the spectra have pronounced peaks near 51, 65 and 103 GHz, which have a fine spectral structure, Fig. 5.12.

The figure also shows the frequency dependence of the imaginary part. complex permittivity of water, associated with the absorption coefficient. The permittivity in this region, as established by P. Debye, is approximately described by the formula

$$\ddot{y}(\ddot{y}) = \ddot{y}\ddot{y} + \frac{\ddot{y}0\ \ddot{y}\ \ddot{y}\ddot{y}}{1 + i\ddot{y}\ddot{y}},$$

where ÿ0 ÿ 80 is the static permittivity, ÿÿ ÿ 1.7 — dielectric constant at optical frequencies, ÿ ÿ 0.7·10ÿ11 s is the parameter, the dielectric relaxation time of water at room temperature. It is clear that absorption does not correlate with excitation spectra of radio wave luminescence of water.

The spectra were obtained at an irradiation power of ÿ1 ÿW/cm2. At high powers, it was difficult to observe such spectra due to the non-stationarity of luminescence. Since the radiation wavelength

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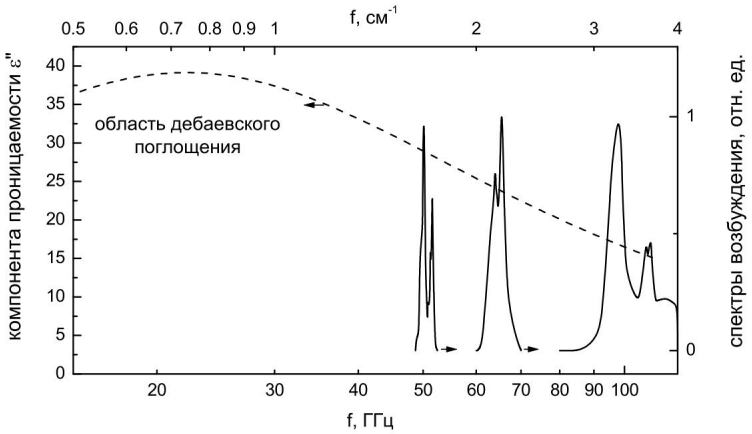


Fig. 5.12: Excitation spectra of radio wave luminescence of water, according to the data of [38], and the spectrum of the reactive component of the dielectric constant associated with the Debye absorption of radio waves.

at a frequency of 1 GHz is equal to 30 cm, then the authors believe that the occurrence radio wave emission is associated with the excitation of the entire volume of water. In at the same time, the Debye absorption of microwave excitation
The absorption coefficient in this region is several tens of cmÿ1, and the exciting radiation is almost completely absorbed by the surface layer.

water with a thickness of about 0.1 cm. The mechanism of conversion of excitation energy into radio wave radiation is not yet clear. The radiation power captured by the radiometer and significantly exceeding the thermal
background, many orders of magnitude less than the absorbed power, at a density microwave energy flux of ÿ1 ÿW/cm2. Therefore, the conversion mechanism is inefficient from an energetic point of view. Note that the mechanism is not associated with the overall heating of the water sample, no matter how small it is.
was, and with the resulting increase in the power of thermal radiation in the radio wave range. The process of heating water with microwaves does not have required frequency selectivity, while the excitation spectra of the effect, on the contrary, are frequency selective.

Radio wave luminescence spectra of water and various fabrics
organisms are similar in that they have peaks in the same spectral ranges near 51, 65, and 103 GHz. As the authors note, this is a consequence of the fact that the tissues of the organism are tens of percent

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stand out from the water. At the same time, the fine structure of the luminescence spectra depends on the physiological state of the organism, which allows use the discovered phenomenon for medical diagnostic purposes [151].

An important observation was that the magnetic field splits the peak near 50 GHz into a Zeeman doublet. The splitting in the field H = 50 Gs was about f ÿ 1 GHz. The equivalent magnetic moment ÿ is related to the indicated quantities by the relation 2ÿH = 2ÿf and is equal to ÿ ÿ 7 10ÿ20 erg/G, which is almost an order of magnitude greater than the spin magnetic moment of the electron. Note that the splitting of the peak and Its origin could be due to the orbital motion of electrons or other charged particles. Thus, the hypothetical collective modes responsible for the excitation of luminescence should have a) natural frequencies in the radio wave range, b) an electric dipole moment, c) a magnetic,

and, consequently, the angular momenta of the transitions. The nature of such excitations is currently unknown. Petrosyan, Zhiteneva and others [198] believe that such excitations may be collective vibrations of linked hexagonal rings formed from sixes water molecules held together by hydrogen bonds. Note that the bond energy of the rings, that is, the energy of 6 hydrogen bonds, is half the energy of interaction of the ring with the environment, about 12 hydrogen bonds. Therefore, it is unlikely that such a speculative a structure of water molecules exists in liquid water as an independent object.

There is currently no information on the decay time of the radio wave. luminescence. It is possible that metastable states of water, induced by magnetic fields and EM radiation are associated with collective excitations that manifest themselves in this interesting phenomenon.

5.4 Molecular Gyroscope

The long lifetime of angular modes is the only serious idealization on which the ion interference mechanism is based. Justifying this idealization is difficult in the model of an ion in a protein capsule.
It is necessary to assume that the ion forms bonds with the capsule walls states of the polaron type. In turn, the justification for the large the lifetime of polaron angular modes requires new idealizations.
A “vicious circle” arises from which it is impossible to break free, no matter

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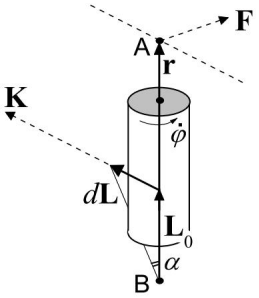


Fig. 5.13: Forces, moments of forces and angular momenta during rotation top.

changing, in a significant part, the model itself. Thus, despite on the obvious advantages of the ion-in-a-capsule model - simplicity and large predictive power, one must acknowledge its limitations and seek other approaches [305].

One of them is related to the use of conservation laws in the dynamics of rotating bodies. The rotation of a rigid body is governed by the equation

$$\frac{dL}{dt} = K \quad , \tag{5.15}$$

where L is the angular momentum, K is the sum of the moments of forces acting on the body. For simplicity, let us assume that we have a symmetrical top rotating around one of its main axes of inertia, and at the point A of support of the top force F acts, Fig. 5.13. The moment of force relative to the specified axis, is obviously equal to zero. From equation (5.15) it follows

$$L = L0 + dL \ , dL = K\,dt = r \times F\,dt \ .$$

Since K ÿ F, then dL ÿ F, that is, the action of the force causes a perpendicular displacement of its own axis of rotation. In addition, vector r is directed along the axis of rotation, therefore vector dL is also perpendicular to L0.

The constant action of the force F thus leads to a forced precession of the top around the direction of F with an angular velocity, determined by the angle of deviation of its own axis of rotation per unit time, that is,

$$\text{ÿprecession} = \frac{dL/L0}{dt} = \frac{K}{L0} = \frac{rF}{L0} \ .$$

The length of the vector r is determined by the conditions of fixing the top. If point B is fixed, then the origin of r coincides with B. If point B is not fixed,

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on, then the beginning of r lies on the line AB and depends on the parameters of the top. For
It is important for the estimates that r is of the order of the length of the top.

Let the top under consideration be a model of a rigid molecule, not constrained in its movements except by thermal vibrations of one of the support points, for example, A. Let us estimate the average angle of deviation of the axis a top, if F is a random force causing chaotic oscillations of the fulcrum. We immediately note that the gravitational energy of the top ÿ MgR is many orders of magnitude less than its kinetic energy ÿ L2/2I and the effects of gravity can be neglected. In the last formulas, M, R, I are the mass, size, and moment of inertia of the top, g is the acceleration gravity.

The energy of the top's own rotation is ÿ0 = L2 0/2I. The energy the top, taking into account the forced chaotic rotations, is, obviously, ÿ0 + ÿT .On the other hand, the average value of energy, taking into account the perpendicularity of L0 and dL, is equal to (angle brackets here mean average by ensemble)

$$\frac{1}{2I}(L0 + dL)^2 = \frac{1}{2I} L2_0 + 2L0dL + d2L = ÿ0 + \frac{d2L}{2I} .$$

Then d2 L/2I ÿ ÿT . Denoting the average deflection angle ÿ = d2L/L0, we find ÿ2 ÿ 2IÿT /L2 0. The smaller L0, the greater the random deviations of the molecule due to thermal disturbances of the support molecules. The support is the covalent bond with the body of the protein matrix. Estimates of the minimum values of L0 follow from the Heisenberg uncertainty relation, which for a complementary pair of non-commuting operators of the angular variable ÿ and angular momentum Lÿ d /dÿ is written as follows

$$L ÿ ÿ /2 .$$

Since ÿ ÿ ÿ, then L ÿ /2ÿ, and accordingly the magnitude of the angular moment cannot be less than its uncertainty, that is, L0 ÿ /2ÿ. Finally, we have

$$ÿ2 ÿ 8ÿ2 \frac{IÿT}{2} .$$

As can be seen, the deviations increase with increasing molecule size, but even for small molecules the deviation estimate is unrealistically large. This means that molecules in lower rotational states will "fall on their sides" when the fulcrum is perturbed, and the angular momentum,

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therefore, will not be conserved. Note that we are interested in angular states with small quantum numbers. Otherwise,
The interference patterns discussed below become fine-grained and are presumably not reflected in any measurable properties.

Thus, in order to acquire immunity to thermal displacements of the supports, it is necessary to also fix the second support in the protein matrix.
top. The design consists of a rotating unit with supports fixed
in the casing, there is one type of *gyroscope,* that is, a device for measuring angular displacements and velocities. In our case, we are talking about
In essence, about the gyroscope at the molecular level: a relatively large molecular group is located in the protein cavity and forms two
covalent bonds (supports) with the cavity walls at their edges. It is important that thermal vibrations of the supports create only zero moments of force
relative to the group's own rotation axis. Therefore, the gyroscopic degree of freedom ÿ is not thermalized. This does not mean that the energy of the gyroscopic degree of freedom does not dissipate.

5.4.1 Radiative damping of molecular gyro-osprey

Molecules suitable for the study of (molecular) interference in
MP must have an electric moment, for example, a dipole moment.
In this case, the relaxation of the energy of the molecular gyroscope has
one of the reasons is the so-called radiation damping or Lorentz friction force. In [121] it is shown that the loss of angular momentum by a system of charges
the dipole radiation count obeys the equation

$$\frac{dL}{dt} = \frac{2}{3c3} dÿ \times d^{\cdot\cdot}, \qquad (5.16)$$

(d is the dipole moment of the system) is valid, as is the approximation of classical electrodynamics itself, under the conditions

$$ÿ \ll Mc2/, \qquad ÿc \ll Mc2/,$$

where ÿ is the radiation frequency, M is the mass of the emitting particle. For masses the scale of molecular masses, the characteristic frequency Mc2/ is of the order of > 1020 rad/s, therefore both inequalities are satisfied with a reserve.

Let the dipole rotate in the xy plane:

$$d = d(nx \cos ÿt + ny \sin ÿt).$$

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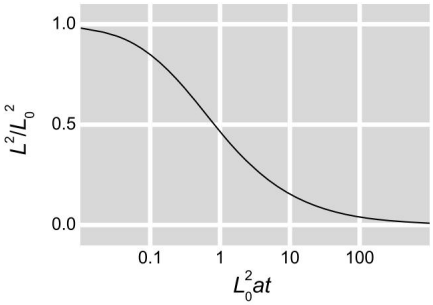


Fig. 5.14: Relaxation of energy
angular momentum of the molecule
dipole radiation account.

Differentiating and substituting into (5.16) we obtain, taking into account the relation L = Iÿ, the following equation

$$L\ddot{y} = \ddot{y}a(L + Lt\dot{y})^3, a = \frac{2d2}{3c3I3},$$

the solution of which aL3t + L = L0 (neglecting terms ÿ L¨ and higher) implicitly determines the dependence of angular momentum on time. The quantity L2/L2 0 is the relative rotational energy of the molecule. Graph dependence of the relative energy on the dimensionless parameter L2 0at is shown in Fig. 5.14. From the graph it follows that the time scale ÿ of attenuation is determined by the equality L2 0aÿ ÿ 1. From where we find, using L0 score

$$\ddot{y}\ddot{y} \frac{1}{aL2_0} = 6\ddot{y}2 \frac{c3I3}{d22}.$$

The order of magnitude of the radiation decay time can be easily calculated from approximate equalities I ÿ MR2, d ÿ eR. For the mass of a molecule in one hundred proton masses with a dipole moment of e·5 Å this time is about 1011 s. Radiative attenuation here is practically zero.

5.4.2 Relaxation time by the molecular dynamics method

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The contribution to relaxation from van der Waals electromagnetic forces generated by wall vibrations can be estimated as follows. The interaction of the gyroscope with the walls, described by the Lennard-Jones potential, decreases with increasing cavity size as
1/r6. At the same time, the surface area of the cavity walls increases as r2. Therefore, the contribution of van der Waals interactions is proportional 1/r4. Energy exchange decreases rapidly with increasing cavity size.

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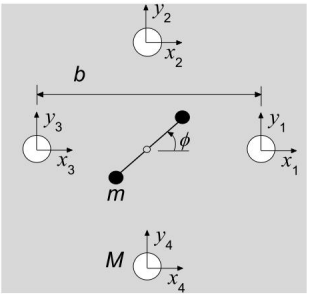


Fig. 5.15: Two-dimensional model motion of a gyroscope (two particles of mass m) in a molecular cavity formed by four heavy particles, b is the diameter cavities, M is the mass of particles.

Computer simulation of rotational dynamics of molecular gyroscope shows that the size of the cavity providing a relaxation time of about 0.01 s is less than 30 A° .[8] This is a quite plausible size for protein cavities.

The amino acid residue phenylalanine (Phe) CÿC6H5 was chosen as the gyroscope. Let us consider the rotation of the benzene ring C6H5 around the Cÿ—Cÿ valence bond. The rotation of this ring can be considered as the rotation in one plane of two rigidly connected point mass m = 26 mp (mp is the mass of a proton), located at a distance of a = 2.42 A° from each other, around their common center of gravity.

We will model the cavity using four massive particles located at the vertices of a square, the center of which coincides with the center of gravity of the gyroscope, see Fig. 5.15. The diameter of the square is b>a, the mass of each particles M ÿ m. We will assume that these particles oscillate in the plane of rotation of the gyroscope xy. The motion of each particle is limited by the potential U(xi,yi), where xi, yi is the displacement of the i-th particle from its equilibrium position. Then the Hamiltonian function of the system under consideration will have the form

$$H = \frac{1}{2} I\dot{\varphi}^2 + \sum_{i=1}^{4} \frac{1}{2} M(\dot{x}_i^2 + \dot{y}_i^2) + V(\dot{\varphi}, x_i, y_i) + U(x_i, y_i), \quad (5.17)$$

where $I = \frac{1}{2} ma^2$ is the moment of inertia of the gyroscope, and ÿ is its angle of rotation.

= The interaction potential of the i-th particle with the gyroscope is the sum two Lennard-Jones potentials

$$V(\dot{\varphi}, x_i, y_i) = \{[(r_0/r_1)^6 \dot{\varphi} 1]^2 + [(r_0/r_2)^6 \dot{\varphi} 1]^2\},$$

where r0 is the equilibrium length between the heavy and light particles, r1 is

8The author is grateful to A.V. Savin for carrying out these calculations.

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the current distance from the i-th heavy particle to the first particle of the gyroscope, and r2 is the distance to the second particle.

To describe the interaction of carbon atoms in polymer macro-
The Lennard-Jones potential is commonly used in chromomolecules.

$$VLJ(r)=40[(ÿ/r)^{12} - ÿ(ÿ/r)^{6}],$$

where ÿ = 3.8 A° and 0 =0.4937 kJ/M [651]. Therefore, given that each particle in the gyroscope consists of two carbon atoms, let's put =1 kJ/M ÿ 20 and r0 =4.5 A° ÿ 21/6ÿ.

We take the substrate potential for each heavy particle in the form

$$U(x, y)= \frac{1}{2}K\,\frac{x2 + y2}{1 - ÿ(x2 + y2)/R0},$$

where K is the rigidity of the interaction of the particle with the substrate, R0 is the maximum possible radius of displacement of a heavy particle. In protein macromolecule the rigidity of displacement of atoms K = 4 N/m. Let's carry out calculations for two values of maximum displacement: R0 = 1 A° And R0 = ÿ.

Let's assume that only heavy particles are associated with the thermostat. Then the system of equations of motion will have the form

$$\begin{aligned} Iÿ^{\cdot\cdot} &= \frac{ÿÿH}{ÿÿ}, \\ Mx^{\cdot\cdot}i &= ÿ\,ÿ\,ÿMxÿ\,i\,\cancel{+ ÿi}, \frac{ÿH}{ÿxi} \\ My^{\cdot\cdot}i &= ÿ\,ÿ\,ÿMyÿi\,\cancel{+ ÿi}, \frac{ÿH}{ÿyi} \\ & i = 1, 2, 3, 4 \quad , \end{aligned} \tag{5.18}$$

where the Hamiltonian function of the system is given by formula (5.17); ÿi and ÿi are random normally distributed forces (white noise) describing the interaction of the i-th heavy particle with the thermostat; the friction coefficient ÿ = 1/tr, where tr is the relaxation time of the particle velocity. Random forces have correlation functions

$$ÿi(t1)ÿj(t2) = 2MÿÿT\,ÿij\,ÿ(t1 - t2),$$
$$ÿi(t1)ÿj(t2) = 2MÿÿT\,ÿij\,ÿ(t1 - t2),$$
$$ÿi(t1)ÿj(t2) = 0 .$$

Here T is the thermostat temperature.

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The system of equations (5.18) was integrated numerically using the standard Runge-Kutta method of the fourth order of accuracy with a constant step integration of ÿt. In numerical implementation, the delta function ÿ(t)= 0 for |t| > ÿt/2 and ÿ(t)=1/ÿt for |t| < ÿt/2, i.e. the numerical integration step corresponded to the correlation time of the random force. Therefore, to use the Langevin system of equations, it was
It is necessary that ÿt tr. Accordingly, the relaxation time is chosen tr = 0.2 ps, and the numerical integration step ÿt = 0.0025 ps.

Let the system be in the ground state at the initial time t = 0. Thus, at the initial time, the molecular gyroscope is not thermalized. Our goal is to estimate the average thermalization time of the gyroscope. It corresponds to the relaxation time of the gyroscope's rotation in a thermalized molecular system.

For this purpose, the system of equations of motion (5.18) was numerically integrated. with the corresponding initial conditions.

Thermalization of a gyroscope at time t is characterized by its ther- fever

$$T1(t)= \frac{I}{\ddot{y}\ddot{y}\ddot{y}2(t)},$$

where the brackets denote the average over independent realizations of random forces ÿi(t), ÿi(t), i = 1, 2, 3, 4. To obtain the average value

The system of equations (5.18) was integrated more than 10,000 times. Further, the thermalization of the system of heavy particles is characterized by the current temperature

$$T2(t)= 8ÿ \frac{M}{} \sum_{i=1}^{4} xÿ^{2}i(t)+ ÿy2(t).$$

At t = 0, temperatures T1(0) = T2(0) = 0. With increasing time, their values monotonically tend to the thermostat temperature T = 300 K. We consider that the molecular subsystem is completely thermalized if its

the current temperature exceeds 0.99T, i.e., the thermalization time ti is solution of the equation Ti(t)=0.99T . The gyroscope is thermalized through interaction with the system of heavy particles, therefore its thermalization time depends on the diameter of the system of heavy particles b and always exceeds the thermalization time of the system of heavy particles (t1 >t2). Time t2 is practically independent of b and depends only on the value of the relaxation time tr: t2 ÿ 4tr.

We considered the dynamics of the system at R0 = 1 Å, ÿ and M = m, 100m. The dependence of the gyroscope thermalization time t1 on the cavity diameter b is shown in Fig. 5.16 for R0 = 1 Å and M = m. Thermalization time grows exponentially with increasing b. If we extrapolate

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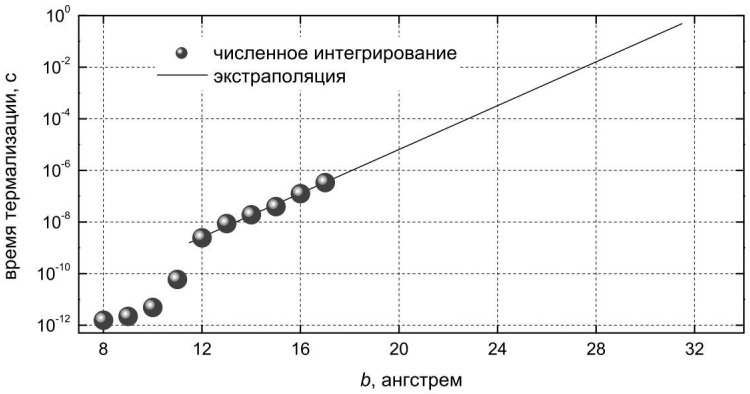


Fig. 5.16: Dependence of the gyroscope thermalization time t1 on the diameter molecular cavity b at M = m, R0 =1 A° and extrapolation of this dependence in the region of large values of b.

dependence in the region of large values of b, then we can conclude that regardless of the values of parameters R0 and M at b = 28–32 A° time thermalization, and therefore the relaxation time of the gyroscope, will be of the order of seconds. With this cavity size, the rotation of the molecular gyroscope is practically free.

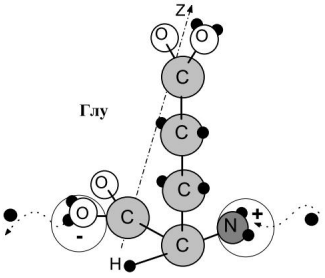
Thus, thermal disturbances of the molecular gyroscope supports do not thermalize its rotational degree of freedom, radiation attenuation small, the attenuation due to van der Waals forces is also small, for cavities of the order of 30 A°. Therefore, the coherence time of the rotational degrees of freedom of ÿ 0.1 s are sufficient for the manifestation of interference effects.

5.4.3 Gyro interference

Rotations of large molecules are much slower than electron processes. and vibrational. Therefore, we will imagine a rotating molecular group as a rigid system of charged point masses (atoms of the molecule with partially polarized chemical bonds). For illustration, we point to amino acid molecules, which could be inserted into fairly spacious protein cavities, forming two chemical bonds at the remote ends of the molecule—a molecular gyroscope.

Amino acids are the building blocks of polymeric protein macromolecules.

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Rice. 5.17: Glu molecule s potentially ionizing groups. Rotation of distribution charges distributed over the molecule in MP leads to interference of it quantum corner states.

cool, and are also present in bioplasma in the form of free monomers. The general formula of amino acids is well known. It is as follows view

$$\begin{array}{c} R \\ | \\ H2N+ ÿ\ CH\ ÿ\ COHOÿ \end{array} \quad ,$$

where R is a radical that distinguishes different amino acids; indicated polarity of groups in an aqueous solution. A radical, for example, glutamic acid consists of three units ÿCH2 ÿ CH2 ÿ COOH, Fig. 5.17. A similar molecule, fixed on both sides in the cavity, as a whole dynamic unit, has one degree of freedom - polar angle ÿ, which simplifies the analysis of its behavior in the MP.

The Lagrange function of one charged particle in the case of low velocities has the form

$$L = +\frac{Mv2}{2} \quad \frac{q}{c} Av\ ÿ\ qA0\ , \tag{5.19}$$

where v is the particle velocity, q is an arbitrary charge. Let MP H = (0, 0,H) is directed along the z-axis, and the particle is bound by a holonomic connection so that it moves in a circle in the xy plane. Equations connections in a spherical coordinate system are written as follows

$$r = R = Const\ ,ÿ = ÿ/2\ . \tag{5.20}$$

We will choose the vector potential in the form

$$A = \quad -1 - Hy,\ 2\ \frac{1}{}\ Hx,\ 0\ .\ 2 \tag{5.21}$$

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The velocity of a particle in a spherical coordinate system taking into account the constraints (5.20) is v = Rÿÿ, and the velocity vector in the Cartesian system is equal to

$$v = (\ddot{\varphi}R\dot{\varphi}\dot{\varphi}\sin(\varphi), R\dot{\varphi}\dot{\varphi}\cos(\varphi), 0) . \quad (5.22)$$

From here, substituting into (5.19), we obtain the Lagrange function in a spherical coordinate system

$$L = \frac{MR^2\dot{\varphi}^2}{2} \quad \frac{qH}{2c} R^2\dot{\varphi}\dot{\varphi} + qA_0 . + \quad (5.23)$$

Let us find the generalized momentum l = ÿL/ÿÿÿ and the Hamiltonian function H = lÿÿ ÿ L.

$$l = \frac{\ddot{\varphi}L}{\ddot{\varphi}\dot{\varphi}\dot{\varphi}} = MR^2\dot{\varphi}\dot{\varphi} + \frac{qH}{2c}R^2 , \quad (5.24)$$

$$H = l\dot{\varphi}\dot{\varphi} \ddot{\varphi} L = MR^2\dot{\varphi}\dot{\varphi}^2 + \frac{qH}{2c}R^2\dot{\varphi}\dot{\varphi} \ddot{\varphi}$$

$$-\frac{1}{2}MR^2\dot{\varphi}\dot{\varphi}^2 - \frac{qH}{2c}R^2\dot{\varphi}\dot{\varphi} + qA_0 = \frac{1}{2}MR^2\dot{\varphi}\dot{\varphi}^2 + qA_0 .$$

It is necessary to express H in terms of generalized coordinates. It is clear from (5.24) that

$$l - \frac{qH}{2c}R^2 = MR^2\dot{\varphi}\dot{\varphi} ,$$

$$(H - qA_0) = \frac{1}{2}MR^2\dot{\varphi}\dot{\varphi}^2 = \frac{1}{2MR^2}M^2R^4\dot{\varphi}\dot{\varphi}^2 = \frac{1}{2MR^2}\left(l - \frac{qH}{2c}R^2\right)^2 .$$

Then

$$H = \frac{1}{2MR^2}\left(l - \frac{qH}{2c}R^2\right)^2 + qA_0 . \quad (5.25)$$

In the absence of an electromagnetic field H = l 2/2MR2, from which it is clear that l is the angular momentum of the particle. The Hamiltonian operator or Hamiltonian repeats (5.25) with the difference that l here is already the angular momentum operator. moment L = ÿiÿ/ÿÿ.

Now let several particles rotate, and the equations of constraints for the i-th particle in the spherical coordinate system has the form

$$r_i = Const , \dot{\varphi}_i = Const .$$

Then, following the derivation of formula (5.23), we write the Lagrange function of a system of particles in a uniaxial magnetic field in the form

$$L = \frac{I}{2}\dot{\varphi}\dot{\varphi} + \frac{HQ}{2c}\dot{\varphi}\dot{\varphi} \quad q_iA_0(r_i,\dot{\varphi}_i,\varphi_i) , \quad (5.26)$$

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Where

$$I = \sum_i Mir2_i \sin2(\ddot{y}i) ,Q = \sum_i qir2_i \sin2(\ddot{y}i) \qquad (5.27)$$

— the moment of inertia and the “moment of inertia of the charge” of the system relative to axis of rotation. It is clear that the Lagrange function of the system is obtained from Lagrange functions (5.23) by formally replacing the coefficient MR2 with I, qR2 by Q and qA0 by the corresponding sum. Therefore, the Hamiltonian system immediately follows from (5.25), where a similar replacement must be made

$$H = \frac{1}{2I} L\ddot{y} 2c \frac{QH}{}^2 + \sum_i qiA0(ri,\ddot{y}i,\ddot{y}i) .$$

Next, we assume that there is no electric field, that is, A0 = 0:

$$H = \frac{1}{2I} L\ddot{y} 2c \frac{QH}{}^2 .$$

Here, in addition to L2/2I, there are two more operators. There are reasons to neglect the quadratic term in H: by composing the ratio of the coefficients of the quadratic and linear terms in H, we find

$$\frac{QH}{} \ddot{y} 10\ddot{y}7 4c , \qquad (5.28)$$

where for the estimates it is accepted that Q ÿ eR2, R ÿ 10ÿ7 cm, H ÿ 1 G. Neglecting this member and taking the following designation

$$\ddot{y} = \frac{QH}{2Ic} , \qquad (5.29)$$

we write the Hamiltonian in a convenient form

$$H = \frac{L2}{2I} \ddot{y} \ddot{y}(t)L . \qquad (5.30)$$

The eigenfunctions and energies of the time-independent part of the Hamiltonian (5.30) are equal to

$$|m = \exp(\text{~~inÿ~~}) ,m =0, \pm1, .. , \ddot{y}2\ddot{y} \qquad \ddot{y}m = \frac{2}{2I} m2 .$$

Let us further consider an ensemble of gyroscopes with a density operator ÿ, obeying the Liouville equation

$$i\ddot{y}\ddot{y} = H\ddot{y} \ddot{y} \ddot{y}H ,\ddot{y} = \sum_{\ddot{y}} w(\ddot{y})\ddot{y}(\ddot{y}) . \qquad (5.31)$$

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Such physical quantities as the intensity of spontaneous or ensemble-scattered radiation depend linearly on the density matrix
ensemble

$$ymm = \sum_{y} w(y)y(y)\ mm \quad .$$

The probability of the biochemical reaction studied here is not a physical quantity of this type. The reaction probability is not directly related to the ensemble density matrix. It is the reaction probability of an individual gyroscope, averaged over the ensemble. Therefore, we find

first the density matrix ÿ(ÿ) $_{mm}$ gyroscope with number ÿ, then prob-

the gyroscope's response, which depends nonlinearly on ÿ(ÿ) $_{mm}$ and, however,

nets, we average the result over the ensemble of gyroscopes.

Let us assume that the ensemble consists of gyroscopes that arise with a constant average speed at random moments in time. Let also new gyroscopes appear in a superposition of states close to to the ground state:

$$y(y)_{mm}\ (0) = \begin{cases} \text{Const}\ , & m, m\ y\ 1 \\ 0\ , & m, m\ y/\ 1 \end{cases} \quad .$$

Thermalization leads to the population of levels with energies up to ym ÿ kB T IkB T ÿ 102 for , ÿ mi of inertia of the order of I ÿ $\frac{1}{}$ gyroscopes with moment-i.e., with numbers up to m 10ÿ37 g cm2 (the moment of inertia of Glu relative to
long axis). However, we are interested in the dynamics of the lowest states - only it is related to the observed effects.

In the representation of the eigenfunctions of H0, the equation for the matrix densities can be written from (5.30) and (5.31) in the form

$$\dot{y}y_{mm} = y(ymm + iymm)ymm\ y \quad \frac{i}{-} \quad (Vmlylm\ y\ yml Vlm\ ) \ , \ (5.32)$$

Where

$$ymm = \frac{}{2l}\ (m2\ y\ m2) \ , \qquad Vml = yy(t)myml \ .$$

The phenomenological relaxation of the density matrix elements is taken into account here through the attenuation coefficients ymm . Due to the relaxation
the ymm elements of the lower modes decrease, while the upper modes increase. Since the stationary dynamics of an individual gyroscope does not represent
for our interest, we do not take into account the pumping of the upper modes in the equation, i.e., redistribution of populations into states with large numbers-
mi m.

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The above relations, when substituted into (5.32), give
equation

$$\ddot{y}\ddot{y} = \ddot{y}\ddot{y}\ddot{y} + i\ddot{y}\,[(m\ \ddot{y}\ m\ )\dot{y}(t)\ \ddot{y}\ \dot{y}]\ ,$$ where the

indices m, m are temporarily omitted for convenience. With the notation

$$g(t)\ \ddot{y}\ddot{y}\ddot{y} + \text{if}\ ,\ f\ \ddot{y}\ (m\ \ddot{y}\ m\ )\dot{y}(t)\ \ddot{y}\ \dot{y}$$

the equation takes the simple form $\ddot{y}\ddot{y} = g(t)\dot{y}$. The constants C in the solution of this equation $\ddot{y} = C \exp \int g(t)\,dt$ are determined by the initial conditions.

If the MP contains both constant and variable components,
shiye, then

$$\ddot{y}(t) = \ddot{y}g(1 + h\cos\ddot{y}t)\ ,\ddot{y}g\ \ddot{y}\ ,h\ \ddot{y}\qquad \frac{QHDC}{2Ic}\qquad \frac{HAC}{HDC}\ .$$

Let us separate the constant and variable parts in g(t)

$$g(t) = \ddot{y}x + iz\ddot{y}\cos\ddot{y}t,\ x\ \ddot{y}\ \ddot{y} + i\ddot{y}\ \ddot{y}\ i(m\ \ddot{y}\ m\ )\ddot{y}g$$

$$hz\ \ddot{y}\ (m\ \ddot{y}\ m\ )\ddot{y}g\ \ddot{y}\qquad \frac{}{} = (m\ \ddot{y}\ m\ )\ \ddot{y}\qquad \frac{h}{}\ ,\quad \ddot{y}\ \ddot{y}\qquad \frac{\ddot{y}}{\ddot{y}g}\ .$$

The integral is equal to

$$\int g(t)\,dt = \int (\ddot{y}x + iz\ddot{y}\cos\ddot{y}t)dt = \ddot{y}xt + iz\sin\ddot{y}t,$$

hence

$$\ddot{y} = \ddot{y}(0)e\int g(t)\,dt = \ddot{y}(0)e\ddot{y}xteiz^{\sin\ddot{y}t} = \ddot{y}(0)e\ddot{y}xt\sum_n Jn(z)ein\ddot{y}t\ .$$

Returning indices m, m , we write down the equation

$$\ddot{y}mm = \ddot{y}mm\ (0)e\ddot{y}[\ddot{y}mm + i\ddot{y}mm\ddot{y}i(m\ddot{y}m\ )\ddot{y}g]t\sum_n Jn(zmm\ )ein\ddot{y}t\ .$$

Further, all attenuation coefficients are assumed to be equal to ÿ. Having designated

$$\ddot{y}\ \ddot{y}\ \ddot{y} + i\ddot{y}mm\ \ddot{y}\ i(m\ \ddot{y}\ m\ )\ddot{y}g\ \ddot{y}\ in\ddot{y}\ ,$$

let's rewrite the last equation in the form

$$\ddot{y}mm = \ddot{y}mm\ (0)\sum_n Jn(zmm\ )e\ddot{y}\ddot{y}t\ ,$$

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which will be used below.

Now we will find the probability density of the gyroscope to have a certain angular position ÿ - the only favorable position for the reaction of the gyroscope with an active site on the cavity wall

$$p(t)=ÿÿ(t, ÿ)ÿ(t, ÿ)= = \frac{1}{2ÿ}\sum_{m} cÿ\, m(t)eÿimÿ \sum_{m} cm\,(t)eim\,ÿ = \frac{1}{2ÿ}\sum_{mm} ÿmmeÿi(mÿm\,)ÿ,$$

those.,

$$p(t)= 2ÿ \frac{1}{mmn} ÿmm\,(0)eÿi(mÿm\,)ÿeÿÿtJn(zmm\,) .$$

It is advisable to perform moving average: relatively fast density oscillations that do not affect the slow reaction with the active site with the characteristic time constant ÿ will disappear,

those.,

$$pÿ\,(t)= 2ÿ \frac{1}{tÿÿ}\int^{t+ÿ} p(t\,)\,dt .$$

In fact, we need to average the factor exp(ÿÿt):

$$eÿÿt \;_{ÿ} = \frac{\sinh(ÿÿ)}{ÿÿ} eÿÿt\,ÿÿ ,$$

That's why

$$pÿ\,(t)= 2ÿ \frac{1}{mmn} ÿmm\,(0)\frac{\sinh(ÿÿ)}{ÿÿ} eÿi(mÿm\,)ÿeÿÿtJn(zmm\,) . \quad (5.33)$$

Then, as in the ion interference model, we assume that the probability of the reaction of the side group of a rotating molecule with the active site of a protein is a nonlinear function of the probability density (5.33). In the absence of any information about this function, it makes sense to take into account the first non-vanishing term, the quadratic one, see [293]. To find the probability of the reaction, we square (5.33) and average over the ensemble of gyroscopes. The product pÿ (t)pÿ (t) includes 1)

complex conjugate terms, pairs with indices n, m, m and ÿn, m , m, which obviously do not oscillate, and 2) rapidly oscillating terms, which we omit in view of subsequent averaging. Omitting also an unimportant numerical coefficient, we write

$$p2_{ÿ}\,(t) \;eÿ2ÿt \sum_{mmn} |ÿmm\,(0)|^{2} \left(\frac{\sinh(ÿÿ)}{ÿÿ}\right)^{2} J2\,n(zmm\,) .$$

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In this expression the multiplier

$$S\ddot{y}_{mmn}\ |\ddot{y}mm\ (0)|^{2}\ \frac{\sinh(\ddot{y}\ddot{y})}{\ddot{y}\ddot{y}}^{2}\ J2\ n(zmm\ )$$

contains a dependence on the magnetic field.

Let the gyroscope arise at time t , then the probability (in unit of time) of reaction at time t is equal to

$$u(t,\ t\ )=\begin{array}{ll} Se\ddot{y}2\ddot{y}(t\ddot{y}t\ ) & ,t\ \ddot{y}\ t \\ 0 & ,\quad t<t\ . \end{array}$$

Assuming that the moments of time t are distributed over the ensemble of gyroscopes in the interval (ÿÿ, ÿ) with a uniform density w (instead of the discrete distribution w(ÿ) in (5.31)), we find the average probability P by integration over the parameter t:

$$P = \lim_{\ddot{y}\ddot{y}\ddot{y}}\ w\int_{\ddot{y}\ddot{y}}^{\ddot{y}} u(t,\ t\ )\ dt = \frac{wS}{2G}\ .$$

In order to relate this value to some observable value, for example, to the concentration of reaction products, we write down the kinetic equation for the number of gyroscopes per unit volume of tissue

$$N\ddot{y} = w\ \ddot{y}\ PN$$

which gives N = w/P = 2ÿ/S in the steady-state regime for the ensemble. Let S0 and N0 denote the corresponding quantities in the absence of a variable magnetic field, i.e., at h = 0. We would like to know the relative change ÿ concentration of reaction products under the action of an alternating magnetic field. This is is the relative number of gyroscopes that have entered into the reaction, i.e.,

$$\ddot{y}\quad \frac{N0\ \ddot{y}\ N}{N0} = 1\ \ddot{y}\ \ddot{y}\quad \frac{S0}{S}\ . \qquad (5.34)$$

Let us now estimate the quantities S and ÿ. We use the following notation:

$$\ddot{y}\ddot{y}\ \ddot{y}\ \ddot{y} + i\ddot{y}\ ,\ \ddot{y}\ \ddot{y}\ \ddot{y}\ddot{y},\ \ddot{y}\ \ddot{y}\ [\ddot{y}mm\ \ddot{y}\ (m\ \ddot{y}\ m\ )\ddot{y}g\ \ddot{y}\ n\ddot{y}]\ddot{y}.$$

Then the expression for S takes the form

$$S = \sum_{mmn}\ |\ddot{y}mm\ (0)|^{2}\frac{\sinh 2\ \ddot{y} + \sin 2\ \ddot{y}}{\ddot{y}2 + \ddot{y}2}J2_{n}\quad (m\ \ddot{y}\ m\ )\quad \frac{h}{\ddot{y}}\quad . \qquad (5.35)$$

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The series in n in (5.35) converges rapidly, so it is mainly the terms with n = 0 and n = 1 that contribute to the reaction probability. At frequencies where the probability reaches its maximum (ÿ = 2m), the contributions of the terms with n = 1 and n = 2 are proportional

$$\frac{\sinh 2(\ddot{y}\ddot{y})}{\ddot{y}2\ddot{y}\,2}\ J2\ 1(h)$$

And

$$\frac{\sinh 2(\ddot{y}\ddot{y}) + \sin 2(6m\ddot{y}g\ddot{y})}{2(2h)\ .\ \ddot{y}\ 2(\ddot{y}2 +}\ J2$$

36m2ÿ2 g) The terms with n = 2 are obviously more than an order of magnitude smaller in the case ÿg > ÿ, i.e., when it makes sense to study the interference at all. Therefore, for approximate estimates, we omit the terms

with n> 1. Next, we consider separately the terms of the sum (5.35) with n = 0 and n = ±1, which we denote by S0, S1 and Sÿ1: S = S0 + S1 + Sÿ1.

Since ÿ is a constant value, the frequency spectrum is determined by divided mainly by the equation ÿ = 0, i.e. for n = 0,

$$\ddot{y}mm\ \ddot{y}\ \ddot{y}g(m\ \ddot{y}\ m\ )=0\ .$$

If m = m then ÿ is indeed equal to zero and the corresponding term of the sum reaches its maximum. That is, only the terms of the sum with remain in S0.
m = m :

$$S0 = \sum_{m} |\ddot{y}mm|\ ^{2}\frac{\sinh 2}{\ddot{y}\ ,m}\ =0,\ \pm 1,\ ..\ .\ \ddot{y}2$$

For brevity, we omit the argument for the elements of the density matrix here and below.

In the case n = ±1 the equation ÿ =0 gives

$$\ddot{y}mm\ \ddot{y}\ \ddot{y}g(m\ \ddot{y}\ m\ )\ \ddot{y}\ n\ddot{y}=0\ .$$

For arbitrary small values of m, m, the frequencies ÿmm fall into the microwave range. The effects of low-frequency magnetic fields are determined by the interference of levels m = ÿm, when ÿmm = 0. Then

$$\ddot{y}g(m\ \ddot{y}\ m\ )+\ n\ddot{y}=0 \qquad ,\ \text{or}\ 2m + n\ddot{y} =0\ .$$

Here m cannot be equal to zero, since then ÿ = 0 for any real frequency ÿ. If the equality 2m + nÿ = 0 holds, one could write:

$$Sn = \sum_{m=0} |\ddot{y}m,\ddot{y}m|\ ^{2}\frac{\sinh 2\ \ddot{y}}{\ddot{y}2}\ J2_{n}\quad 2m\ \frac{h}{\ddot{y}}\quad .$$

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However, by choosing a specific frequency ÿ ÿ from the series ÿ2m/n (maximum condition) interference maxima), where m = ±1, ±2, .., equivalent to the series 2m, we, thus, we fixed the specific value mÿ = ÿnÿ ÿ/2. Therefore, only one term remains in Sn :

$$Sn = |ÿmÿ,ÿmÿ| \quad 2\frac{\sinh 2\ ÿ}{ÿ2} J2\ n(nh\ ) .$$

It is easy to see, taking into account the relations |ÿmÿ,ÿmÿ | = |ÿÿmÿ,mÿ | and J2 ÿ1(ÿx)=J2 1(x), such that Sÿ1 = S1. Now S = S0 +2S1. Note that in the absence of a variable magnetic field, i.e. when h = 0, S1 = 0. Substituting the expressions found into (5.34), we obtain

$$ÿ =1\ ÿ\ 1+ \quad \frac{2|ÿm,ÿm|^{2}}{m\ \ |ÿm,m(0)|^{2}} J2\ 1(h\ )^{-1} .$$

As can be seen, the magnitude of the magnetic effect depends on the elements of the density matrix at the initial moment of time after the appearance of the gyroscope. For example, if at t = 0 the components of the first rotational state are equally populated, then ÿ0,0 = 0, ÿ1,1 = 1, ÿÿ1,ÿ1 = 1, ÿ1,ÿ1 = 1 (total the multiplier is unimportant), from where

$$ÿ =1\ ÿ \quad \frac{1}{1+J2\ 1(h\ )} . \qquad (5.36)$$

This function is close to the function shown by the line in Fig. 4.45 and even approximates the experimental data in the region of the second maximum somewhat better. If the ground state and states m = ±1, then

$$ÿ =1\ ÿ\ 1+ \frac{1}{\frac{2}{3} J2\ 1(h)} .$$

For equally populated ground level and components of the first k rotational levels

$$\sum_{m} |ÿm,m(0)|^{2} = 1 + 2k$$

And

$$ÿ =1\ ÿ\ 1+ \frac{1}{\frac{2}{1+2k} J2\ 1(h\ )} .$$

It can be concluded that the positions of the maxima of the amplitude spectrum do not depend, and their relative values depend on the initial population distributions by gyroscope levels.

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The spectrum ÿ = 2m determines only the possible positions of the frequency extrema. The actual shape of the spectrum depends on the initial conditions for the density matrix, i.e., on the population of levels with different
rotational quantum number m.

Note that for the magnetic interference effect to appear,
The molecule does not necessarily have to have a dipole moment i qiri. It is important that the "moment of charge inertia" Q (5.27) is non-zero. This
can also occur in the absence of a dipole moment, for example, for
ionic rather than zwitterionic form of the molecule.

The main properties of gyroscope and ion interference are the same:
— polyextremality of amplitude and frequency spectra,
— dependence of the positions of the frequency spectra peaks on the magnitude of the constant magnetic field,
— independence of the positions of the amplitude spectrum maxima from the frequency of the alternating magnetic field.

The interference of a molecular gyroscope differs from the interference of bound ions. Firstly, the frequencies of the frequency maxima
spectrum are associated with the rotational frequency ÿg - the rotational equivalent of the cyclotron frequency. These frequencies depend on the distribution of the electric charge density in the molecule and can differ
from harmonics and subharmonics of the cyclotron frequency. Secondly, the axis of rotation of the molecular gyroscope is fixed with respect to the cavity
protein, this generally gives another averaging parameter. However,
These differences are not fundamental. Specific interference spectra can always be calculated for any configuration of magnetic and electric fields, also taking into account their own
rotations of protein molecules, organelles, cells and entire biological systems.

The most important property of molecular gyroscope interference is its relative insensitivity to molecular
thermal disturbances. Molecular gyroscopes can be an effective biophysical target for the action of external magnetic fields.

From (5.35) it is evident that the absolute value of the magnetic effect, when it is maximized by selecting the parameters of the magnetic field, depends mainly on
way from the value ÿ = ÿÿ, which must be minimal for
the possibility of significant effects. The protein reaction time ÿ and the MP frequency ÿ must satisfy the relation ÿÿ> 1 in order for
interference became noticeable. This relationship (together with the properties of the function sinh2 ÿ/ÿ2) leads to the condition of observability of magnetic

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effects

$$ÿÿ1 > ÿÿ1 ÿ 0.01 \text{ s} \quad (5.37)$$

in the low-frequency range.

■ As one of the probable mechanisms of MBE, the molecular interfering gyroscope claims to be a solution to the “kT problem”. Indeed, the walls of the protein cavity do not interact with the gyroscopic degree of freedom directly, by short-range chemical connections. The contribution to relaxation from van der Waals electromagnetic forces generated by wall vibrations is small and depends on cavity size. Numerical simulation of the gyroscope dynamics shows that the gyroscope rotation relaxation time tr increases exponentially with increasing cavity diameter b in Fig. 5.15. Thus, for a gyroscope, formed by the amino acid residue phenylalanine (Phe) CÿC6H5 in a cavity with a diameter of 33 $\overset{o}{A}$, the relaxation time exceeds 1 s. Radiative attenuation is negligible. Finally, the oscillations of the gyroscope supports create zero torque relative to the axis of rotation and do not affect the angular momentum. The gyroscopic degree of freedom is thermalized. very slowly, its dynamics are coherent, and this allows it to manifest itself slow interference effects. Of course, the very existence of more or less water-free cavities with a radius of about 15 $\overset{o}{A}$ and more constitutes a question, but, what is essential, is no longer a paradox. catfish

Perhaps the role of molecular gyroscopes could be performed by short sections of polypeptide chains and nucleic acids embedded inside globular proteins or in the cavities between associated globules. In this regard, the Watson-Crick pairs of nitrogenous bases adenine-thymine and guanine-cytosine, which bind DNA strands in a double helix and other hydrogen-bonded complexes of nitrogenous bases. Their rotation is hindered by steric factors. However, in the area of action of special DNA enzymes, steric restrictions can be removed, allowing relatively free rotation of molecular complexes. It is still unclear whether In general, molecular structures like a gyroscope. They are unlikely to be detectable by X-ray methods. The latter require crystallization. proteins for X-ray structural analysis. But in this state, the rotations are most likely frozen. If rotations do occur, then The moving groups do not give clear cues. Some other ones are needed methods that work specifically with native forms of proteins, undistorted by crystallization.

The fact that the molecular gyroscope is physically consistent is explained

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This is a scientific fact about MBE, indirectly indicating its reality. Future research will show whether this is true. However, at present, the molecular interfering gyroscope is the only mechanism simultaneously transparent from the point of view of physics and consistent in main features of the experiment.

5.5 Unsolved problems of magnetobiology

gyi

The specific behavior of frequency and amplitude spectra depends on a large number of factors, even within the framework of a relatively simple ionic model. interference. In general, the most obvious factors are are:

— nonlinearity of transformations of the primary target signal of the MP in the chain of biophysical and biochemical transformations,

— multidirectional response of different target ions in specific magnetic conditions,

- the participation of several magnetoreception mechanisms at once in one and the same the same biological system,

— dependence on the initial conditions of the ion in the macromolecular capsule, which in turn are mediated by the conformational state of the molecules, and, consequently, by such physical quantities as temperature and pressure. Other aspects that determine the conformational state and metabolism are genetic modifications within a single biological species, the concentration of substances, and the targets of the magnetic resonance.

The presence of many of these factors, their complex interrelationships, makes the observation of MBE, which is in good agreement with theoretical predictions, an experimental stroke of luck, in a certain sense a clever find by the experimenter. The search for experimental models of this kind, which are little sensitive to factors other than the MP, seems to be an important task. It is precisely these biological systems could form a regular basis for deepening knowledge about the physical nature of MBE.

Another, unfortunately sad, conclusion is the limited the suitability of most experimental models of MBE for clarifying the physical nature of the phenomenon. It is clear that from theoretical You shouldn't expect much from these models. The task of the theoretical model here is to give *a correct* explanation of the nature of a particular mechanism of the MBE. For the above reasons, this *prin-*

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the validity follows (assuming the model is consistent from a physical point of view) from agreement with only a limited circle
specially designed experiments.

Today it can be stated that the main characteristic features
The MBEs have been reliably established in numerous experiments and are well reproducible in different experimental models and under different magnetic conditions. These are:

- polyextreme character of both frequency and amplitude
MBE spectra,
— biological effectiveness of magnetic vacuum conditions,
— proportionality of effective frequencies to harmonics and subharmonics
cyclotron and sometimes NMR frequencies of various atom-ions,
— paradoxically low energy of magnetic fields causing biochemical and biological responses.

The theory of ion-molecular interference turns out to be capable
explain these general patterns of the phenomenon of magnetobiological
reception. The basis of the explanation is the involvement of angular
quantum states of atoms and ions and rotational states of molecules
in the magnetic field. Such states represent de Broglie waves in angular coordinate space on a microscopic scale and are capable of interfering with each other, forming slowly rotating nodes and antinodes of the particle. The stability of the interference pattern with respect to thermal vibrations of the medium is explained by the peculiarities of their interaction with angular and rotational states. The theory of ion-molecular interference leads to several

general form of the end-to-end "field-effect" formulas and leaves the possibility of their verification by experiment. Calculations using these formulas, carried out
for magnetic conditions of a number of known experiments, show good agreement with them.

It is more or less clear why relatively strong MPs, in contrast
from weak ones, rarely cause noticeable biological effects. This is due to the fact that the magnetic field does not exert a forceful effect on the particles. More
a strong field leads to large phase shift frequencies that do not coincide in order of magnitude with the natural frequencies of ions and therefore
does not entail a new quality in the system. Thus, Glaser, Michalski and Shramek [447] conducted a detailed study of the effect of EMF on the membrane calcium pump in human erythrocytes. In the low-frequency
range at a magnetic field level of more than 1 mT of bright biological effects
not detected. Obviously, fields of this level go beyond the boundaries of possible interference mechanisms, Fig. 5.18.

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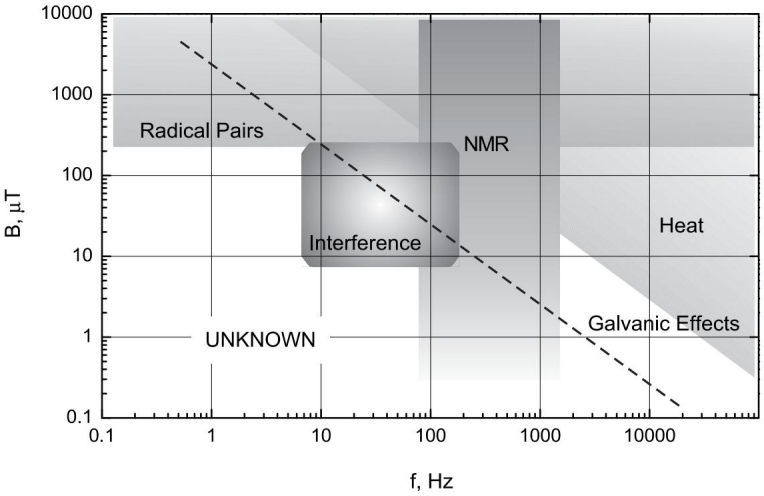


Fig. 5.18: Approximate amplitude-frequency limits of action
possible mechanisms of MBE.

Naturally, any one mechanism, or even a group of mechanisms based on one idea, is unlikely to be able to explain
all the diversity of accumulated experimental data. Probably,
In different ranges of magnetic fields, different principles of magnetic reception by biological objects operate. For example, for relatively high levels
For magnetic fields of 1 mT and above, mechanisms utilizing magnetosensitive reactions with free radicals are likely. It should be noted that this idea remains unconfirmed in experiments specifically designed for this purpose.

Based on the data presented in the book, it can be concluded that unresolved problems of magnetobiology of the physical plane are
are:

— identification of MP targets in well-reproducible MBEs,
— mechanisms of biological action of moderate constant MPs,
- clarification of the role of water and water memory in MBE,
— mechanisms of stability of ionic interference in relation to
thermal disturbances of the environment,
— search for mechanisms of biological action of ultra-weak, less
1 ÿT, MP,
— solution to the problem of social regulation of background MP in the conditions

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the action of frequency- and amplitude-selective mechanisms of magnetoreception,

- targeted impact of EMF on selected physiological
(biochemical) subsystems,
— delivery of complexly organized MPs to local areas of biological systems,

- general methods of correction of immune processes by low-frequency
magnetic fields,
— development of methods for active protection against background unfavorable
radiation,
- specific mechanisms of action of MP on biological processes
communications - intercellular, population, interspecies, etc.
— and their use for population management.

A common weakness of magnetobiological experiments is the relatively small number of measurements when varying the MF parameters. This, generally speaking, does not allow one to draw reliable conclusions about the presence of spectral peaks of the effect, since in this case there is a possibility that in the interval between two adjacent points there will be some other spectral feature if

corresponding measurements. The author is aware of only a few works
in the field of magnetobiology, which satisfy the rules of spectral measurements accepted in physics. Therefore, conducting regular
spectral measurements in magnetobiology that could be
the confidence to approximate smooth curves remains one of
unresolved problems.

There are very few experiments that have been designed for
a definitive answer to any question about the nature of the physical processes of the primary act of magnetoreception. In the overwhelming majority of cases, experiments that clearly demonstrate the presence of MBE,
carry very little information about the physics of the processes. It would be advisable to use in magnetobiology the experience of setting up physical experiments and testing statistical hypotheses of a physical nature. Methodologically, it is correct to formulate the hypothesis in such a way that the experimental results unambiguously point to one

from two equilibrium physical situations. A number of interesting experiments were proposed by Engstrom and Fitzsimmons [424]. They propose to establish the general characteristics of the physical process of magnetoreception: the speed, the nature of the acting field and the spatial distribution of the MF targets. The setting up of such unambiguously interpretable experiments could lead to a rapid solution to the problem.

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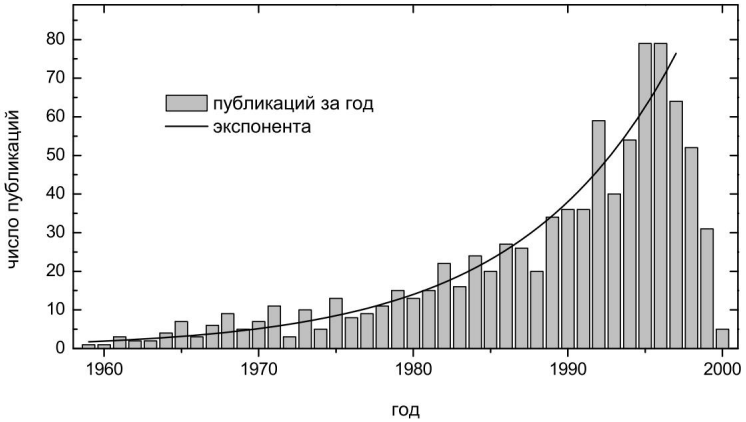


Fig. 5.19: Distribution of the number of publications per year by time, plotted according to the bibliography from this book. Distribution in the interval up to 1997 years approximated by an exponential function.

problems of magnetobiology.

While working on the book, the author reviewed several thousand original works on electromagnetic biology and related topics.
The bibliography contains approximately seven hundred titles. A work was included in the list if, from the author's perspective, it contained results that were significant for the topic.

No other selection criteria were used. Therefore, the list of references could serve as the basis for a small statistical
research. The distribution of the number of publications was of interest
by time, which usually reflects the dynamics of scientific development
directions, of course, in addition to the natural process of loss of social significance by individual publications with a characteristic time
15–20 years. However, the topic of the book—the physics of magnetoreception in biosystems —is completely new today. Therefore, there are no outdated publications yet, and the distribution of the number of publications is quite indicative of the development of the topic itself.
from the state of pseudoscience to the state of cutting-edge research, albeit with
with difficulty, but already appearing on the pages of recognized scientific journals
catch.

Figure 5.19 shows the growth of publication density over time.

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Since a total of about 30,000 works have been published, we conclude that in recent times several thousand articles on this topic have been published annually in the world Electromagnetic biology. Exponential growth over the past decades is quite natural. Many natural social processes in the first stage of their development, when there are no restraining factors. This may be followed by relative stabilization or even a decline in the intensity of the process. This occurs for many reasons, in particular, due to the loss of social significance of research due to the successful solution of the problem, or, conversely, due to protracted failures in its solution. Author I am inclined to believe that the peak in the number of publications occurred in 1995–1996. absolute. This means that the decrease in the intensity of publications in In recent years, this has been due not only to the natural 2-3 year delay in citing scientific literature, but also to the objective state of the problem of fundamental processes of magnetoreception itself biological systems.

The decline in research intensity is due, firstly, to the completion in the USA in 1998 of a multi-year program (RAPID) of research into human health in connection with chronic exposure to background electromagnetic fields of industrial frequency (it is recognized that Low frequency electromagnetic fields represent a potential threat to human health). Secondly, the decline is due to significant a reduction in the flow of publications in the USSR, which constituted a significant part of the work in this field. Finally, the effect of unfulfilled expectations of society regarding an acceptable physical explanation of the nature of the observed effects.

Apparently, the stage of extensive accumulation of empirical data is being completed. The biological patterns of action of electromagnetic fields have been generally established. At the same time, the knowledge gained is entirely empirical in nature; there is no understanding of the nature of the patterns discovered. This is due to the fact that the overwhelming majority of studies had a substantially biological focus and were not aimed at identifying the physical essence of the interaction. EMF and living systems. The content is indicative in this regard The major annual conference BEMS-2000, held in Munich, featured approximately 100 papers and 220 poster presentations. Only one paper (by the author) addressed the theory of the primary mechanism of biological sensitivity to weak EMFs.

Magnetobiology, as a developing science, is currently experiencing a number of objective difficulties. The difficulties are rooted in

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significant underdevelopment *of the theory* of magnetobiology. Outlining the history of the discovery of the oscillatory chemical reaction, the Belousov reaction, Zhabotinsky, Shnol [218] writes: *We notice and declare as a phenomenon only that which we understand, for which a theory already exists. But for the construction of a theory there must be an "order"—the presence unexplained phenomenon. Breaking this vicious circle requires enormous intellectual and moral efforts...* Apparently, these words are equally applicable to magnetobiology.
The natural way to overcome the "vicious" situation would be to develop theory and experiment in parallel, side by side. However, there is significant predominance of the magnetobiological experiment over theory.

■ Academic interest in the problem of magnetobiology is restrained
The lack of a clear physical explanation. Therefore, magnetobiology exists primarily through financial contributions from interested companies that manufacture equipment based on EMF radiation. The interest of such companies is to demonstrate the harmlessness of, for example, cell phones and household electrical equipment, or, conversely, the high therapeutic efficacy of certain biomedical electromagnetic technologies. In both cases, there is a social imperative that regulates the scope of electromagnetic modes being studied within fairly narrow boundaries. The leading scientific journal "Bioelectromagnetics" is filled with articles on the biological effects of EMFs only at industrial frequencies of 50 and 60 Hz.

and some GHz frequencies of mobile communications. Obviously, as a specific The practical focus of the social order, as well as its frequency-amplitude limitations, do not allow for the effective study of the physical nature of the MBE.

Finally, another difficulty is that magnetobiology, falling, on the one hand, simultaneously into the fields of physics and biology, on the other hand, it does not fall entirely into either of them. This complicates the publication of articles on the physical problems of magnetobiology. Biological journals typically experience quite natural difficulties with reviewing articles with a substantive physical content. This is precisely how frankly weak articles on MBE mechanisms appear on their pages. At the same time, physics journals still remain skeptical about the possibility of the influence of weak magnetic fields on biological systems. Opponents among physicists often argue for their negative attitude

only because the effects explained in the peer-reviewed articles are

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are known for their irreproducibility, so there simply cannot be a subject for discussion. Nevertheless, physics journals are beginning to publish positive papers on the mechanisms of MBE [576, 305].

The very concept of magnetobiology implies in a certain way in a sense, the necessary equal representation of both biological and physical sciences. However, the current state of the problem is such that physics in magnetobiology is in its infancy. There is a dramatic imbalance between the physical and biological contributions. This contradiction is currently the main
The driving force behind the development of magnetobiology. The magnetobiological branch of theoretical biophysics is just beginning to emerge. The priority is to carry out work that summarizes the accumulated material, putting forward working hypotheses on the biophysical mechanisms of magnetoreception, development of experiments aimed at definition of the primary physical processes of transformation of electromagnetic signals into biochemical level signals. The author considered I would have solved my problem if this book had been useful incentive for future research of this kind.

Moscow, 1996–2000

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Chapter 6

Applications

6.1 Angular momentum operators

Transformations of spherical and Cartesian coordinate systems have next view

$$x = r \sin ÿ \cos ÿ,\ y = r \sin ÿ \sin ÿ,\ z = r \cos ÿ$$

And

$$r = \sqrt{x2 + y2 + z2},\ ÿ = \arccos \frac{z}{r},\quad \tan ÿ = \frac{y}{x}.$$

Differentiating the equations for x, y, z successively with respect to r, ÿ, ÿ, semi-what

$$\frac{ÿ(x, y, z)}{ÿ(r, ÿ, ÿ)} = \begin{matrix} \sin ÿ \cos ÿr & \cos ÿ \cos ÿ ÿr & \sin ÿ \sin ÿ \\ \sin ÿ \sin ÿr & \cos ÿ \sin ÿr & \sin ÿ \cos ÿ \\ \cos ÿ & ÿr \sin ÿ & 0 \end{matrix}.$$

Differentiation of equations for r, ÿ, ÿ successively with respect to x, y, z gives

$$\frac{ÿ(r, ÿ, ÿ)}{ÿ(x, y, z)} = \begin{matrix} \sin ÿ \cos ÿ & \sin ÿ \sin ÿ & \cos ÿ \\ \frac{1}{r} \cos ÿ \cos ÿ & \frac{1}{r} \cos ÿ \sin ÿ & -\frac{1}{r} \sin ÿ \\ -\frac{ÿ}{r \sin ÿ} & \frac{\cos ÿ}{r \sin ÿ} & 0 \end{matrix}. \qquad (6.1)$$

By definition, the angular momentum operator is $L = ÿir \times ÿ$:

$$Lx = ÿiy\left(\frac{ÿ}{ÿz} - ÿz \frac{ÿ}{ÿy}\right),\ Ly = ÿiz\left(\frac{ÿ}{ÿx} - ÿx \frac{ÿ}{ÿz}\right),$$

$$Lz = ÿix\left(\frac{ÿ}{ÿy} - y \frac{ÿ}{ÿx}\right).$$

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Using (6.1), we have

$$Lx = i\sin\ddot{y}\ \frac{\ddot{y}}{\ddot{y}\ddot{y}\ \ddot{y}} + i\cos\ddot{y}\cot\ddot{y}\ \ddot{y}\ddot{y}\ \frac{\ddot{y}}{\quad},$$

$$Ly = \ddot{y}i\cos\ddot{y}\ \frac{\quad}{\ddot{y}\ddot{y}\ \ddot{y}} + i\sin\ddot{y}\cot\ddot{y}\ \ddot{y}\ddot{y}\ \frac{\ddot{y}}{\quad},$$

$$Lz = \ddot{y}i\ \ddot{y}\ddot{y}\ \frac{\ddot{y}}{\quad}, \qquad L\pm = Lx \pm iLy = e\pm i\ddot{y}\pm\ \frac{\ddot{y}}{\ddot{y}\ddot{y}\ \ddot{y}\ddot{y}} + i\cot\ddot{y}\ \frac{\quad}{\quad},$$

where the formula is also applied

$$\frac{\ddot{y}}{\ddot{y}xi} = r_{xi}\frac{\ddot{y}}{\ddot{y}r} + \ddot{y}_{xi}\frac{\ddot{y}}{\ddot{y}\ddot{y}} + \ddot{y}_{xi}\frac{\ddot{y}}{\ddot{y}\ddot{y}}.$$

6.2 Lande multiplier for ions with spin nuclei

The magnetic splitting factor in relatively weak magnetic fields, or the Lande multiplier, in the case of ions with nuclear spin, depends on the charge, mass, spin, and magnetic moment of the ion. In the central potential, the spin-orbit interaction operator is proportional to the product of the nuclear spin operators I and the orbital mechanical moment L. This operator is expressed as a linear combination of the squared operators of the spin, orbital, and total moments, J = I + L, that is, it commutes with each of them. Therefore, the proper

the functions of the Hamiltonian of an ion in a central potential, taking into account the spin-orbit interaction, can be chosen to be common for the indicated operators: spin-orbit, and the squares of the moments, as well as for the operator of the projection of the total moment commuting with them
Jz. Let such functions be functions ‖lijm, where l, i, j, m —
quantum numbers of the orbital, spin, total, and projection total angular momentum. The magnetic Hamiltonian of the ion is ÿMH, the operator
the magnetic moment of the ion is equal to

$$M = (bL + \ddot{y}I) = b(L + 2\ddot{y}I),$$

where ÿ is the ion-isotope constant. Following the technique described, for example, in [70], we represent the operator M in the form M = GJ as the product of the total , that is, in momentum operator J by a certain scalar
operator G that needs to be found. We have the operator equality

$$GJ = b(L + 2\ddot{y}I).$$

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Since J = I + L, then

$$GJ = b(J + (2ÿ ÿ 1)I) .$$

Multiplying the last equality by J as a scalar, we obtain

$$G = b\ 1 + (2ÿ ÿ 1)\frac{(JI)}{J^2} .$$

By virtue of the operator identity

$$2J\ I = J^2 + I^2 ÿ L2 ,$$

which is obtained by squaring the expression L = J ÿ I, the relation for G takes the form

$$G = b\ 1 + (2ÿ ÿ 1)J\ \frac{^2 + I^2 ÿ L2}{2J^2} .$$

Since the functions |lijm are eigenfunctions for the operators included in this expression, they are also eigenfunctions for the operator G. In a homogeneous MP

The Hz magnetic Hamiltonian of the ion is ÿMH = ÿMzHz = ÿGJzHz.

Obviously, its matrix elements are diagonal and the corrections to the energy levels that determine their splitting in the MP are equal to

$$ÿlijm = lijm| ÿ GJzHz|lijm = ÿmbgHz , \qquad (6.2)$$

where we find the Lande multiplier g by substituting its proper operator for G

nal values:

$$g = 1 + (2ÿ ÿ 1)\frac{j(j + 1) + i(i + 1) ÿ l(l + 1)}{2j(j + 1)} . \qquad (6.3)$$

It differs from the g-factor of an electron in an atom by the presence of a coefficient 2ÿ ÿ 1 in front of the fraction in (6.3). For an electron ÿ= ÿM c/Sq =1, which reduces (6.3) to the standard definition.

Ion-isotope constant required to calculate the multiplier

Lande, and other properties of ions important for the functioning of biological systems are given in Table 6.1. The dimensional values in the table are given in the CGS system.

Lande multiplier values for some biologically important

ions with nuclear spin are given in the following tables.

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Table 6.1: Magnetic properties of some cations

at.v.Ionspin M/q C, T1/2			ÿ0	fc/fN	$\frac{\mu}{\mu N}$/ÿ
1H1/2	1.008/1 4781	1522/4261	2.793/2.80	99.99 0.016	2393 761.7/654
2H1	3.016	0.8574/0.86	2.014 12.32 y	1598 508.7/4544	2.979/8.93
3H1/2	6.015/1 801.2	255.0/627	0.822/2.46	7.59 686.9	218.7/1656
6Li1	3.256/7.57	7.016 92.41	21.99/1 2.61 y	69.8/444	1.746/6.36 219.2 209.6
7Li3/2	23.99 14.96 h	260.3 128	2.218/16.9	22.99 100	63.9/322 1.690/5.04
22Na3	23.99/2 78.99	401.8 127.9	331.7	122.8/261 24.99 10.0	25.98 11.01
23Na3/2			118.1		
24Na4					
24 mg					
25Mg5/2					0.855/2.12
26Mg					
35Cl3/2	34.97/1	75.78	**137.8**	43.9/418	0.8219/9.53
37Cl3/2	36.97	24.22	**130.4**	41.5/348	0.6841/8.38
39K3/2	38.96/1	93.26	123.7	39.4/199	0.3915/5.06
40K4	39.96	0.0117	120.6	38.4/248	1.298/6.45 37.5/109
41K3/2	40.96	6.73	117.7	0.215/2.92	
40Ca	39.96/2 96.94		241.2	76.8	
43Ca7/2	42.96	0.145	224.4	71.4/287	1.317/4.02
45Ca7/2	44.96	163 d	214.4	68.2/289	1.327/4.23
55Mn5/2	54.94/2	100	175.4	55.8/1053	3.453/18.86 163.6
59Co7/2	58.93/2	100	52.1/1008	4.627/19.37	24.4/1130
63Cu3/2	62.93/1 69.17			2.223/46.37	76.6
65Cu3/2	64.93 30.83		28.6/1211	2.382/51.26	74.2 150.8
64Zn	63.93/2 48.63		146.2 46.5		
66Zn	65.93 27.90	66.93	45.8/267		
67Zn5/2	4.10 84.91/1			0.8755/5.83	144.0
85Rb5/2	72.17 86.91	27.83	18.1/413	1.355/22.88	56.8
87Rb3/2	132.9/1 100		17.7/1399	2.751/79.25	55.5
133Cs7/2			11.5/563	2.582/48.78	

I is the spin of the ion nucleus, M, q is the mass in amu and the charge of the ion, C is the abundance of the isotope in %, T1/2 is the half-life, ÿ is the magnetic moment nuclei, frequencies ÿ0 are Larmor, fc are cyclotron and fN are NMR frequencies, are given for a magnetic field of 1 G (100 ÿT), ÿ=ÿN /ÿc is the ion-isotope constant. Negative numbers are shown in bold.

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Hydrogen 1H, i =1/2, ÿ=2.80

l\j 0	1/2	3/2	5/2	7/2
	5.6			
	-0.533 2.533			
1		0.08	1.92	
2 3			0.343 1.657	

Lithium 7Li, i = 3/2, ÿ = 7.55

l\j	1/2	3/2	5/2	7/2 9/2
0		15.1		
1	24.5	11.34 9.46		
2	-13.1 3.82	6.237 7.043		
3		-7.46 1.403	4.357 5.7	

Sodium 23Na, i = 3/2, ÿ = 16.88

l\j 0	1/2	3/2	5/2	7/2	9/2
1		33.76			
	55.6	25.02 20.66			
	-31.76 7.552	13.17 15.04			
2 3		-18.66 1.936		8.8	11.92

Magnesium 25Mg, i = 5/2, ÿ = ÿ2.124

l\j	1/2	3/2	5/2	7/2	9/2	11/2
0			-4.248			
1		-6.347	-3.648 -2.749			
2	-11.25	-3.548	-2.449 -2.082 -1.916			
3	9.747	0.65 -0.649	-1.083 -1.279 -1.385			

Potassium 39K, i =3/2, ÿ=5.055

l\j	1/2	3/2	5/2	7/2	9/2
0		10.11			
1	16.18	7.681	6.466		
2	-8.11	2.822	4.384 4.904		
3		-4.47	1.26 3.169	4.037	

6.3 Magnetic resonance

The wave function of a particle with spin 1/2 is a first-rank spinor

ÿ = $\begin{matrix} ÿ1 \\ ÿ2 \end{matrix}$ with components ÿ1 and ÿ2. The main property of spinors,

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What distinguishes them from other mathematical objects are certain laws of their transformation when rotating the coordinate system.
The components of the spinor ÿ in the rotated coordinate system are defined the following relationship

$$ÿ = Uÿ ,$$

where U is a unitary matrix (U The $^{+}$ = U ÿ1) with unit determinant.
rotation operator by an angle ÿ around the direction n for the wave function of a particle with spin S is [122]

$$Un(ÿ) = \exp(iÿnS) .$$

In particular, for spin 1/2 the rotation operator around the axis a = x, y, z
is equal to Ua(ÿ) = exp(iÿÿa/2), where the Pauli matrices ÿ =2S have the form

$$ÿx = \begin{matrix}01\\10\end{matrix} ,ÿy = \begin{matrix}0\ ÿi\\i\ 0\end{matrix} ,ÿz = \begin{matrix}10\\0\ -1\end{matrix} .$$

Expanding the exponential in a series and noting that all even powers of the Pauli matrices are the identity transformation, and the odd ones are simply equal to ÿa, we obtain

$$Ux = \begin{matrix}\cos\frac{ÿ}{2} & i\sin ÿ\frac{}{2}\\ 2i\sin ÿ\frac{}{2} & \cos\frac{ÿ}{2}\end{matrix} ,Uy = \begin{matrix}\cos\frac{ÿ}{2} & \sin ÿ\frac{}{2}\\ 2ÿ\sin ÿ\frac{}{2} & \cos\frac{ÿ}{2}\end{matrix} .$$

$$Uz = \begin{matrix}eiÿ/2 & 0\\ 0 & eÿiÿ/2\end{matrix} . \qquad (6.4)$$

Magnetic resonance described by the equation

$$iÿ=ÿ Hÿ \quad , \quad H = ÿÿS\ H = ÿÿH^{-1}\frac{}{2} \qquad (6.5)$$

takes place in the so-called precessing magnetic field

$$Hx = h\cos(ÿt) ,Hy = h\sin(ÿt) ,Hz = H,$$

where H is the value of the constant and h is the amplitude of the alternating magnetic field.
It is convenient to move to a coordinate system rotating around the z-axis with frequency ÿ. The operator of such a rotation, denoted for convenience by one letter, has the form

$$Uz(ÿt)= Z = \begin{matrix}eiÿt/2\ 0 & 0\\ & eÿiÿt/2\end{matrix} .$$

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In this case, the spinor ÿ in the new coordinate system is equal to

$$ÿ = Zÿ .$$

Substituting this into (6.5), we obtain the equation of spin dynamics in a rotating coordinate system

$$ÿÿ = H ÿ \quad , \quad H = ÿ \quad \frac{i}{} ZHZÿ1 + ZZÿ ÿ1 \quad . \tag{6.6}$$

Note that in the new coordinate system the Hamiltonian H , as well as MP, does not depend on time. Therefore, the solution of the equation is simplified. Multiplying the matrices gives

$$ÿÿ = \frac{i}{2} Aÿ \ ,A = \begin{matrix} ab \\ b ÿ a \end{matrix} \ ,a = ÿH + ÿ, b = ÿh . \tag{6.7}$$

The eigenvectors of the matrix A are equal to

$$ÿ0 = \begin{matrix} b \\ -f \end{matrix} \ ,ÿ1 = \begin{matrix} f \\ b \end{matrix} \ ,f = a ÿ ÿ \tag{6.8}$$

$$ÿ = \sqrt{a2 + b2} \ ,ÿ0 = ÿ, ÿ1 = ÿÿ.$$

Here ÿ0,1 are the eigenvalues of the vectors. The solution of the equation is a superposition

$$ÿ = \sum_k ckeiÿkt/2ÿk \ ,$$

and the wave function in the original coordinate system is equal to

$$ÿ= Zÿ1ÿ = \sum_k ckeiÿkt/2Zÿ1ÿk . \tag{6.9}$$

Of the four real quantities that determine the complex coefficients ck, only three are independent, since there is a normalization condition |ÿ|^2 =1. Further, the common phase of the coefficients has no physical content. The choice of the two remaining values determines the initial state of the spin wave function. Let the spin state coincide at t = 0. with the eigenfunction of the operator ÿz ÿ1 = $\begin{matrix} 1 \\ 0 \end{matrix}$. In this state the projection of the spin onto the z-axis has a certain value of 1/2. From the equalities

$$ÿ(0) = c0ÿ0 + c1ÿ1 = c0 \begin{matrix} b \\ -f \end{matrix} + c1 \begin{matrix} f \\ b \end{matrix} = \begin{matrix} 1 \\ 0 \end{matrix}$$

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we'll find

$$c0 = b/ÿ , \qquad c1 = f /ÿ , ÿ = f \quad {}^{2} + b2 .$$

The normalization of ÿ(t) is ensured by the normalization of the initial value function states. Let's now find how the probability will change over time.
detect the spin in the state ÿ0. This is obviously the square of the modulus of the corresponding coefficient in the expansion of the wave function ÿ(t) into superposition of ÿ0 and ÿ1:

$$p0 = |ÿ0|ÿ(t)|2 .$$

Calculating[1] this value gives

$$p0 = \frac{2f\ 2b2}{} (1 ÿ \cos ÿt) = (1 ÿ \frac{b2}{\cos ÿt}) , ÿ2\ 2ÿ2 \qquad (6.10)$$

where the equality fb/ÿ = ÿb/2ÿ is used. From (6.7) and (6.8) we find that the frequency of oscillations of the probability of spin states, the Rabi frequency, is equal to on

$$ÿ = \sqrt{(ÿH + ÿ) \quad {}^{2} + (ÿh) \quad {}^{2}} .$$

The amplitude of the oscillations reaches its maximum (magnetic resonance) when the Rabi frequency is minimal. In this case, the frequency of the external field is equal to frequency of free spin precession in MP H:

$$ÿ = ÿÿH = ÿ0 .$$

Let us find the quantum mechanical averages of the spin projection operators onto different axes

$$Si = 2 \quad \frac{1}{} \quad ÿ(t)|ÿi|ÿ(t) = 2 \quad \frac{1}{} \quad \underset{km}{} cÿ\ kcme ÿi(ÿkÿÿm)t/2ÿk|ZÿiZÿ1|ÿm . \qquad (6.11)$$

Omitting, as before, the intermediate calculations, we write down the result for the magnetic resonance situation:

$$Sx = \sin ÿ0t \sin(ÿht) \frac{1}{2} \qquad (6.12)$$

$$Sy = \frac{1}{2} \cos ÿ0t \sin(ÿht)$$

$$Sz = \frac{1}{2} \cos(ÿht)$$

[1]The scalar ÿ|ÿ is calculated according to the rule ÿ|ÿ = ÿ+ÿ =(ÿ1)ÿÿ1 +(ÿ2)ÿÿ2.

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A conceptual "spin vector" with Si components rotates around
z-axis so that its end describes spiral trajectories on the surface of a sphere of radius 1/2.

The spin vector can only be discussed in a conditional or statistical sense. Since the operators of spin projections onto different axes
do not commute, then the corresponding observable quantities cannot
take on certain values simultaneously. Thus, the spin vector is not an observable quantity in the quantum mechanical sense. Note that there are more than ten different systems of postulates or interpretations of quantum mechanics that make up

the subject of research in the so-called quantum metaphysics [683]. Interpretations differ in meaning and relationships of unobservable quantities, and, in essence, are attempts to eliminate the internal difficulties of the theory
— the so-called paradoxes of quantum mechanics. It is important that, with respect to observable quantities, all interpretations give the same predictions. In
One interpretation of quantum mechanics assigns the status of a real state to the spin vector, which is unobservable in an experiment. However, measuring any of its components inevitably destroys the state itself.
state, so that measuring other components becomes impossible. Next, we adopt the statistical meaning of the term "spin vector"
and we use it without quotation marks.

In classical mechanics, the derivative of the mechanical moment of a system is equal to the moment of the forces acting on the system. On the mechanical moment S, associated with the spin vector S in a constant magnetic field H, acts moment M × H, where M = ÿS is the “vector” of the magnetic moment
back. Therefore

$$S\ddot{y} = \ddot{y}0\ n \times S\ ,\ddot{y}0 = \ddot{y}\ddot{y}H\ ,$$

where n is a unit vector in the direction of H. The equation means that
vector S rotates with angular velocity ÿ0 around the direction of the magnetic field without changes in the absolute value of the vector and the angle it forms with the direction of the magnetic field. Such motion is called precession, or, in the case of precession of the orbital momentum of the system, Larmor precession. Generally speaking, precession of orbital and spin angular momenta, for example,
electron, occurs with different frequencies, eH/2mec and ÿH = eH/mec
accordingly. Spin precession is often also called Larmor precession in the literature.

If at some point in time t0 the variable field is switched off, then
phases ÿht in (6.12) will take fixed values ÿ = ÿht0. Subsequently,

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The spin motion is described by the equations

$$Sx = \frac{1}{2}\sin\ddot{y}0t\sin\ddot{y},\ Sy = \frac{1}{2}\cos\ddot{y}0t\sin\ddot{y},\ Sz = \frac{1}{2}\cos\ddot{y}.$$

It is easy to see that these expressions correspond to the precession of a vector with components Si around the direction H z at an angle ÿ, which is justifies the use of the vector spin model.

In general, one can write spin states in which the spin projection has certain values ±1/2 at an arbitrary direction ÿ, ÿ:

$$|+ = \begin{matrix}\cos\frac{\ddot{y}}{2}\\ e^{i\ddot{y}}\sin\frac{\ddot{y}}{2}\end{matrix},\ |\ddot{y} = \begin{matrix}\ddot{y}e^{\ddot{y}i\ddot{y}}\sin\frac{\ddot{y}}{2}\\ \cos\frac{\ddot{y}}{2}\end{matrix}, \qquad (6.13)$$

which are eigenstates of the spin operator

$$S\ddot{y},\ddot{y} = \frac{1}{2}\begin{matrix}\cos\ddot{y}e^{\ddot{y}i\ddot{y}}\sin\ddot{y}\\ e^{i\ddot{y}}\sin\ddot{y}\ \ddot{y}\cos\ddot{y}\end{matrix}. \qquad (6.14)$$

This operator is obtained from Sz by the appropriate rotations. If the spin state in the old coordinate system was defined, with a projection of 1/2 on the z-axis, then in order for the state in the new coordinate system to be characterized by a projection of 1/2 on the axis in the direction ÿ, ÿ, the coordinate system must be rotated around the z-axis by an angle of ÿÿ and then — around the new y-axis by an angle of ÿÿ. The spin operators Si are transformed at the first rotation into $S_i = Uz(\ddot{y}\ddot{y})SiU_z^{-1}(\ddot{y}\ddot{y})$, where Uz is defined in (6.4). The second rotation leads to the desired operator (it should be taken into account that $S_z = Sz$)

$$S\ddot{y},\ddot{y} = Uy(\ddot{y}\ddot{y})SzU_y^{-1}(\ddot{y}\ddot{y}),\ Uy(\ddot{y}\ddot{y}) = \exp(\ddot{y}i\ddot{y}S\ y).$$

Calculations yield (6.13), (6.14). Naturally, at ÿ = 0 we return to the original operator Sz = ÿz/2 and its eigenfunctions.

The coefficients ck in (6.9) are related to the choice of the wave function in initial moment of time. In the general case, it should be chosen in the form, for example, |+. In this state, the spin has a projection of 1/2 onto the direction ÿ, ÿ. This corresponds to the situation when the spin ensemble is not prepared in any special way: the a priori state of the spin is in a certain sense arbitrary. Then

$$\ddot{y}(0) = c0\ddot{y}0 + c1\ddot{y}1 = c0\begin{matrix}b\\ -f\end{matrix} + c1\begin{matrix}f\\ b\end{matrix} = \begin{matrix}\cos\frac{\ddot{y}}{2}\\ e^{i\ddot{y}}\sin\frac{\ddot{y}}{2}\end{matrix},$$

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from which the general expression for the coefficients ck is

$$c0 = \frac{1}{\ddot{y}} \; b \cos \frac{\ddot{y}}{2} \; \ddot{y} \; f \sin \quad \frac{\ddot{y}}{2} ei\ddot{y} \; , c1 = \quad \frac{1}{\ddot{y}} \; b \sin \frac{\ddot{y}}{2} ei\ddot{y} + f \cos \quad \frac{\ddot{y}}{2} \; .$$

Substituting this into (6.11), we find

$$Sz = \frac{b2 \; \ddot{y} \; f^{\;2}}{2\ddot{y}2} \quad b2 \; \ddot{y} \; f^{\;2} \cos \ddot{y} \; \ddot{y} \; 2bf \sin \ddot{y} \cos\ddot{y} +$$

$$+bf \quad 2bf \cos \ddot{y} \cos \ddot{y} + b2 \sin \ddot{y} \cos(\ddot{y} \; \ddot{y} \; \ddot{y}) \; \ddot{y} \; f \; \ddot{y}2 \quad ^{2} \sin \ddot{y} \cos(\ddot{y} + \ddot{y}) \, ,$$

where $\ddot{y} = \ddot{y}t$ is denoted. We rewrite the time-dependent part as follows

$$Sz = r \quad \frac{bf}{\ddot{y}2} \sin(\ddot{y} + \ddot{y}) \, , r2 = (b2 + f \, 2) \, 2 \; x + 4b2f \, 2 \; y + 2bf(b2 \; \ddot{y} \; f \, 2) \; z,$$

$$x = \sin 2 \; \ddot{y}, \; y = \cos 2 \; \ddot{y} \; \ddot{y} \sin 2 \; \ddot{y} \cos\ddot{y}, \; z = \sin 2\ddot{y} \cos\ddot{y}.$$

It can be shown that the extremes of the oscillation amplitude are determined by solutions of the following equation for the parameter $p = f/b$

$$p6 \; \ddot{y} \; 3 \; \frac{z}{x} p5 + (1 + 8 \quad \frac{y}{x}) p4 + 10 \; \frac{z}{x} p3 \; \ddot{y} \; (1 + 8 \quad \frac{y}{x}) p2 \; \ddot{y} \; 3 \; \frac{z}{x} p \; \ddot{y} \; 1 = 0 \quad (6.15)$$

and in general do not coincide with the usual resonance condition $f = \ddot{y}b$, following from the chain of equalities $\ddot{y} = \ddot{y}\ddot{y}H \; \ddot{y} \; a = 0 \; \ddot{y} \; \ddot{y} = b \; \ddot{y} \; f = \ddot{y}b$, see (6.7), (6.8). For $\ddot{y} = 0$, the equation reduces to $p2 = 1$, one of the solutions of which is the usual resonance condition. If, for example, $\ddot{y} = \ddot{y}/2$, $\ddot{y} = 0$, then the oscillation amplitude under the condition $f = \ddot{y}b$ is equal to zero. It reaches maxima at other frequencies. They can be found by solving equation (6.15) for given values of the angles: $(f/b)2 = 3 \pm 2 \; \ddot{y}2$.

The motion of the spin under arbitrary initial conditions is complex nature. If the frequency of the external field coincides with the natural frequency of spin precession, then $f = \ddot{y}b$, and

$$Sz = \quad \frac{1}{-} (\cos \ddot{y} \cos \ddot{y} \; \ddot{y} \sin \ddot{y} \sin \ddot{y} \sin \ddot{y}) \, . \, 2 \qquad (6.16)$$

It is important that the amplitude of the oscillations of the spin projection on the z-axis depends on the initial conditions. Note that if we took into account the random phase $\ddot{y}$ of the precession of the external magnetic field, then in the last expression it would appear as an additional term in one of the arguments. Instead $\ddot{y} = \ddot{y}t$ should be written $\ddot{y}t + \ddot{y}$.

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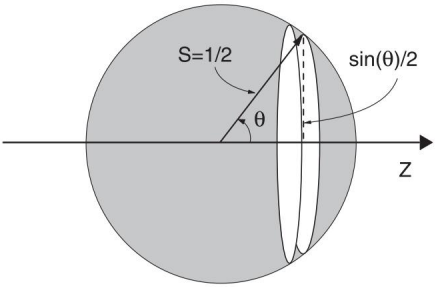


Fig. 6.1: Towards the definition of density the probability of spin tilt at an angle ÿ to the z-axis.

In a constant magnetic field of the geomagnetic field level, the Zeeman splitting ÿ0 is many orders of magnitude smaller than ÿT, which means that possible spin states are equally probable or there is no a priori information about the state of the particle. The a priori uncertainty of the spin state in the ensemble is reduced to the assertion that each individual spin has all directions in space as equally probable. We find the probability density of different values of ÿ and s ÿ Sz.

The probability of a spin having a certain tilt from ÿ to ÿ + dÿ to the axis z is the relative solid angle cut by the difference between the cones with guides ÿ and ÿ + dÿ, Fig. 6.1

$$dP = \frac{2ÿ \sin ÿ \, dÿ}{4ÿ} = \frac{1}{-} \sin ÿ \, dÿ \, 2 \qquad (6.17)$$

From here we immediately find the probability density of the values of ÿ

$$f(ÿ) \, ÿ \quad \frac{dP}{dÿ} = \frac{1}{-} \sin ÿ.2 \qquad (6.18)$$

If the spin is directed at an angle ÿ to the z-axis, then

$$Sz = \frac{1}{2} \cos ÿ \quad , \quad ds = \frac{-1}{2} \sin ÿ \, dÿ = ÿdP. \qquad (6.19)$$

Thus, substituting (6.17), we obtain

$$\frac{dP}{ds} = 1 \quad , \quad \frac{-1}{2} \, ÿ \, s \, ÿ \quad \frac{1}{2} \, . \qquad (6.20)$$

The minus sign is omitted because it only indicates that Sz decreases with increasing angle ÿ. As can be seen from the figure in Fig. 6.2 (line a), the value $Sz = \frac{1}{2} \cos ÿ$ is uniformly distributed in the interval [ÿ0.5, 0.5].

Now let the spin system be in resonance with an alternating magnetic field. If the initial state of the spin is determined, then the oscillations

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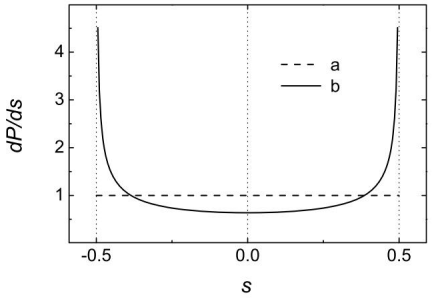


Fig. 6.2: Density distribution of the spin projection values s = Sz on the z-axis under thermal conditions dynamic equilibrium - a, under magnetic resonance conditions — b.

s ÿ Sz is a sinusoidal process (6.16) with random phase ÿ ÿ [0, 2ÿ), the distribution function of which is equal to [512]

$$\frac{dP}{ds} = \frac{2}{ÿ\ ÿ1\ ÿ\ 4s2}, \qquad (6.21)$$

shown in Fig. 6.2 (line b). It is significantly different from the equilibrium distribution, the spin vector is predominantly oriented
along the MP axis. If the initial state is not defined, then in (6.16)
Not only ÿ (ÿ) are random, but also the angles ÿ, with distribution (6.18), and ÿ with uniform distribution. It can be shown that
for such a process the distribution of dP/ds does not differ from the equilibrium distribution of Fig. 6.2 (a). It follows from this that the MBE mechanism,
in principle, could be associated with a change in the distribution function dP/ds under magnetic resonance conditions. However, this is only possible if there is some certainty in the state of the spins. Such
Certainty arises in a number of cases in reactions involving free radicals in MP [35].

6.4 Evaluation of EP gradients on the surface cells

To estimate the EP gradients caused by the external field, we use methods of continuous media electrodynamics. The latter operates with physical quantities averaged over "physically infinitesimal" volume elements. That is, changes in fields due to the atomic-molecular structure of matter are not taken into account; the fields are considered

averaged on a scale significantly exceeding the size of the molecules of the substance.

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This approximation is applicable in particular for the evaluation of characteristics EP near biological cells immersed in a plasma solution. EP gradients induced by an external field near the surface of cell membranes can affect the cells located in these
in some places there are ion-protein complexes.

A dielectric cylinder in a dielectric medium will serve as a model of a biological cell in the cytoplasm. Let the length of the cylinder L be much greater than its radius R, which will allow us to obtain estimates for the particular
cases of different cylinder orientation.

Let us first consider the case where the y-axis of the cylinder is perpendicular to the applied field G z. The LR condition allows us to solve a two-dimensional problem. We will distinguish between the external EF G and the field E, which is a superposition of the external field and the field created by the polarized field
it by a cylinder. We introduce the index e to denote quantities related to the environment, and the index i for the region inside the cylinder. In [123] it is shown,
that the field potentials outside and inside the cylinder have the form

$$ÿe(r)= ÿGr + AGr/r2 \;,ÿi\ (r)= ÿBGr \quad , \qquad (6.22)$$

where r is the radius vector measured from a point on the axis of the cylinder, A, B — constants. Only such potentials satisfy the two-dimensional
Laplace equation for potentials outside and inside the cylinder with the necessary boundary conditions.

At the interface between two dielectrics, the known conditions of continuity of potential and continuity of normal to must be met.
surface component of the induction of the EP D = ÿE, where ÿ is the permittivity. That is, in our case

$$ÿe(R)= ÿi\ (R) \;,ÿeEe(R)= ÿi\ Ei\ (R) \;,$$

here R is a vector of fixed length R. The first condition gives B =
1 ÿ A/R2 and, therefore,

$$Ei\ (r)= ÿÿÿi\ (r)= G(1 ÿ A/R2) \;.$$

The electric field outside the cylinder is equal to

$$Ee(r)= ÿÿÿe(r)= G ÿ Aÿ(Gr/r2) \;.$$

Because

$$ÿ(Gr/r2)=(Gÿ)r/r2 = rÿ2G ÿ 2rÿ4(rG)r \;,$$

That

$$Ee(r)= G(1 ÿ A/r2)+(rG)r2A/r4 \;. \qquad (6.23)$$

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The value of A follows from the condition of equality of normal components induction D at the interface. The normal component of the induction inside the cylinder is equal

$$Di\ n(r)= Di\ (r)r/r = ÿi\ Ei\ (r)r/r = ÿi\ (1\ ÿ\ A/R2)Gr/r\ . \qquad (6.24)$$

The normal component of the induction outside is equal to

$$De\ n(r)= De(r)r/r = ÿeEe(r)r/r\ .$$

Substituting here Ee(r) from (6.23), we find

$$De\ n(r)= ÿe(Gr)(1 + A/r2)/r\ . \qquad (6.25)$$

Equating (6.24) and (6.25) for r = R, we obtain

$$\frac{A}{R2} = \frac{ÿi\ ÿ\ ÿe}{ÿi + ÿe}\ . \qquad (6.26)$$

Now we can find the gradients of the EP on the surface of the cylinder r = R. We will find them in two special cases when the vector r is directed along the z-axis, r = (0, 0,R), and along the x-axis, r =(R, 0, 0). In these cases, there are only z-components of the field Ee. In the x-direction, from (6.23) and (6.26), we have Ee(r)= G(1 ÿ A/r2), from which we find

$$(Ez)_x = \frac{2G}{R}\frac{ÿi\ ÿ\ ÿe}{ÿi + ÿe}\ .$$

Similarly, we find the field gradient in the z direction

$$(Ez)_z = -2\frac{G}{R}\frac{ÿi\ ÿ\ ÿe}{ÿi + ÿe}\ .$$

When ÿe ÿi , which is the case for biopolymers (ÿi ÿ 3) in aqueous is in solution (ÿe ÿ 80), the order of magnitude of the gradients is

$$E\ ÿ\ 2G/R\ . \qquad (6.27)$$

Now let's consider the case of orientation of the cylinder along the field. Interest represents the gradient level on the lateral surface, since the relative area of the cylinder ends is small. The field E of such a cylinder, polarized by an external field G, is close to the field of a dipole. The charge density in a dielectric is determined by the relation ÿ = ÿÿP, where
P is the polarization vector of the medium or the dipole moment of a unit volume

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dielectric. It follows that the surface charge density ÿ
at the interface between two dielectrics is equal to the sum of the normal components of the polarization vector: ÿ = Pi $_n$ + Pe$_n$. For a long cylinder, the polarization P of the dielectrics is parallel to the lateral surface of the cylinder. Therefore, the surface charge density is zero and the field E outside is the sum of the uniform external field G and the polarized field cylinder with effective charges q at the ends. The gradients are obviously are determined only by this last field, close to the dipole field, then there are charges ±q at a distance L.

For the surface charge at the ends we write

$$P_{i,e} = \frac{ÿ_{i,e} ÿ 1}{4ÿ} G \quad , \quad ÿ ÿ = \frac{ÿ_e ÿ ÿ_i}{4ÿ} G.$$

Therefore, the effective charge of the cylinder ends is equal to

$$q = ÿR^2ÿ = GR^2(ÿ_e ÿ ÿ_i)/4 .$$

It is not difficult to calculate the dependence of the EP on the distance r to the dipole axis

$$E_r = \frac{2q}{ÿ_e} r(r^2 + L^2/4)ÿ^{3/2} .$$

Taking the derivative and substituting q, we find

$$(E_z)_x = \frac{4G}{L} \frac{ÿ_e ÿ ÿ_i}{ÿ_e} \left(\frac{R}{L}\right)^2 + o\left(\frac{R}{L}\right)^3 .$$

If ÿ$_e$ ÿ$_i$, then we have the estimate

$$E ÿ \frac{4G}{L} \left(\frac{R}{L}\right)^2 . \qquad (6.28)$$

Comparing with (6.27), we conclude that with a parallel orientation of the cylinder, the magnitude of the gradients is significantly, as (R/L)2 1, less than with orientation perpendicular to the field.

6.5 Parameters of biological tissues

In isotropic dielectrics, the electric induction vector is parallel to the electric field strength vector D ÿ ÿE. If the external field is quickly changed, then due to the inertia of polarization effects (the molecules of the medium must reorient themselves), the change in electric

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Table 6.2: Electrical parameters of biological tissues

frequency [MHz] 10	900	ÿ 0
fabric\parameter		ÿ [S/m]
stomach		0.52
fat	13 0.029 5.4 0.051 98 0.90 59 1.3	0.02
gallbladder		
bile	120 1.4 70 1.8	
leather	360 0.20 41 0.87 70 0.12 21 0.34	0.036
spongy bone	36 0.042 12 0.14 19 0.010 5.5	0.081
compact bone	0.040	0.020
bone marrow		
blood	280 1.1 61 1.54 320 0.75	0.7
uterus	61 1.3	
brain, pituitary gland	180 0.16 39 0.59 460 0.38 49 1.3	0.068
cerebellum		
muscle	150 0.67 57 1.0	0.24
liver		0.52
nerve	220 0.32 47 0.9	0.037
pancreas		0.094
full lung	120 0.23 22 0.46 370 0.51 59 1.4	0.07
bud		0.09
prostate	250 0.78 61 1.2	0.42
cornea	260 0.87 55 1.4	
ligaments		0.28
spleen	440 0.51 57 1.3	
sclera	210 0.80 55 1.2	0.50
gray matter	320 0.29 53 0.9	
heart	290 0.50 60 1.2	0.5
salivary gland		0.52
vitreous body	70 1.50 69 1.6	1.5
sp.-brain fluid	110 2.0 69 2.4	2.0
tendon	100 0.41 46 0.72	
colon	270 0.49 58 1.1	
small intestine	490 1.34 59 2.2 98 0.22 36 0.5	0.090
lens, cartilage,	180 0.37 43 0.78	0.26
pineal		0.17
gland		0.068
thyroid gland, thymus tongue	160 0.72 60 1.0	
	210 0.57 55 0.94	
testicle		0.42

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induction will not occur immediately. This delay or dielectric relaxation time is one of the fundamental physical
properties of matter.

Often the external field is a sinusoidal process. Delay
then leads to a change in the amplitude and phase of the response in relation to to those values that would be observed in the case of a very low frequency, when relaxation can be neglected. Disregarding the vector
notations, which is not important now, we write the EP in the form E sin ÿt. According to but as has been said, electrical induction is equal

D = ÿE sin(ÿt+ÿ)= ÿ E sin ÿt+ÿE cos ÿt, ÿ = ÿ cos ÿ, ÿ = ÿ sin ÿ. (6.29)

There are two pairs of quantities: ÿ, ÿ and ÿ ,ÿ, which equally correctly represent the delay effect. In practice, however, they use
the values of ÿ ,ÿ, since the response components are phase-shifted by 90o, describe different physical processes. In addition, if we introduce complex quantities for fields and relative permittivity ÿ, then relations (6.29) become convenient and universally applicable.
type used

$$D = \ddot{y}Ee^{\tilde{}}\, i(\ddot{y}t+\ddot{y}) =(\ddot{y} + i\ddot{y})Ee^{\tilde{}}\, i\ddot{y}t$$

or

$$D^{\tilde{}}\, \ddot{y} (\ddot{y} + i\ddot{y})E.$$

Table 6.2 shows the values of the complex relative
dielectric constant of different biological tissues for
two frequencies, 10 and 900 MHz. Data adapted from the interactive Internet resource (see [443]) that allows one to obtain the values of ÿ ,ÿ for any frequency from the range of 10–6000 MHz. The table shows also the values ([361], at a frequency of 60 Hz) of the specific electrical conductivity of tissue ÿ, which connects the EP strength and the density of the current generated by it j = ÿE.

6.6 Davydovsky soliton

The concept of the Davydov soliton is associated with the transfer of excitation energy of the C=O bond of peptide groups along the ÿ-helical regions of protein chains. All protein macromolecules are formed by sequences of 20 amino acid residues connected by the so-called peptide groups –C:O–N H–. One of the possible conformations of the polypeptide chain, possessing minimal potential energy,

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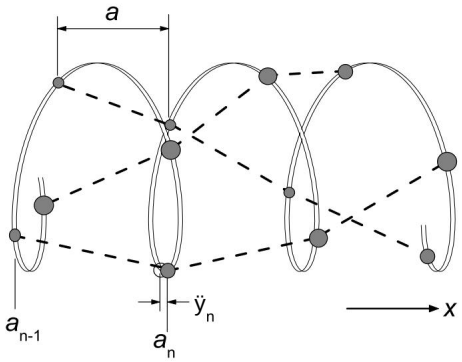


Fig. 6.3: Arrangement of peptide groups in the ÿ-helix molecule. Hydrogen bonds between groups are shown as dotted lines. There are 3.6 peptide groups per turn of the helix, so the chains of hydrogen bonds,
only three, form spirals of large period.

- this is the so-called Pauling–Corey ÿ-helix. Conformational energy of the chain is determined by hydrogen bonds between valence-unbound atoms of the chain. Each peptide group forms a hydrogen bond with the same
the fourth group. The spatial arrangement of the peptide groups is shown in Fig. 6.3. For one reason or another, the polypeptide chain can be deformed. In this case, the peptide groups

are shifted by distances ÿn from their equilibrium positions an.

Infrared vibrational vibrations of C=O peptide groups of ÿ-helices with frequencies near 1650 cmÿ1, which have received the special name Amide I, have a significant transition dipole moment, d ÿ 0.3 D. Therefore, there is an interaction of Amide I vibrations

neighboring peptide groups, which leads to the emergence of collective excitations. Since the dipole interaction strongly depends on
distances, ÿ rÿ3, then the deformation of the polypeptide chain and the propagation of C=O excitations turn out to be interconnected.

The probability amplitude of the amide I vibration in the peptide group with number n is described by the function ÿn(t). In the continuous approximation
the distribution of these probabilities along the chain and in time can be conveniently described by a plane wave

$$\ddot{y}(x, t) \exp [i(kx \ddot{y} Et/)] ,$$

where E is the excitation energy, k is the wave number. In an idealized infinite chain, due to its translational symmetry,

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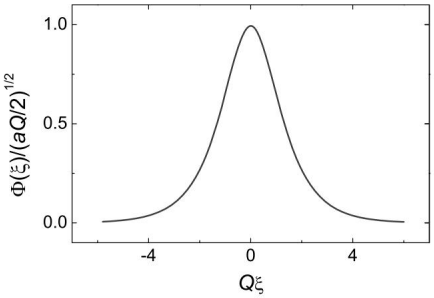


Fig. 6.4: Soliton shape solutions of a nonlinear equation Schrödinger.

The velocity V of excitation propagation along the circuit is stored. Therefore, it is convenient to transition to a moving coordinate system ÿ = x ÿ Vt. Davydov showed, see, for example, [72], that stationary excitations Amide I is described by the nonlinear Schrödinger equation

$$\frac{2}{}\frac{d2}{dÿ2\ 2a2J}\ÿ(ÿ)+ Gÿ3(ÿ) = ÿÿ(ÿ)\ ,m = \ ,G = .\ (6.30)\qquad \frac{}{ÿ(1\ ÿ\ s2)\ 2m}\qquad \frac{2}{}\qquad \frac{}{ÿ2}$$

Here J = 2d2/a3 ÿ 7.8 cmÿ1 is the energy of resonant interaction vibrations of Amide I, ÿ ÿ 10ÿ10 n is the coupling constant between vibrations Amide I and displacements ÿ, ÿ ÿ 19 N/m is the elasticity coefficient of the helix, s is the ratio of the excitation propagation velocity V to the velocity sound in the circuit, a =4.5 Å — period of peptide groups.

The solutions of (6.30) are the envelopes ÿ(ÿ) and the corresponding values of the spectral parameter ÿ. If the speed V is greater than the speed of sound, that is, s2 > 1, then there are only so-called exciton solutions

$$ÿ(ÿ)=1/\ ÿ\ N,\ ÿ=\ ÿG/N\ ,$$

where N 1 is the number of elements in the chain. The propagation of Amide I excitations is described by plane waves. The wave packet formed by excitons spreads out over time; they cannot serve as energy carriers.

For low speeds V , s2 < 1, in addition to the exciton solution, there is also a soliton solution in the form of a hyperbolic secant sch(x)= 2/ [exp(x) + exp(ÿx)],

$$ÿ(ÿ)=\ aQ/2\ \overline{\ \ \ }\ sch(Qÿ)\ ,\qquad ÿ=\ \frac{2Q2}{2m}\ ,Q=\ \frac{maG}{22}\ .$$

The form of this function is shown in Fig. 6.4. Unlike excitons, a soliton moves at a speed less than the speed of sound and therefore does not emit

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phonons and is not slowed down. The propagation of excitation occurs without loss of shape. It is important that the energy of a low-velocity soliton is less exciton energy. The energy difference corresponds to the millimeter range of electromagnetic radiation [86].

A more realistic model takes into account that not one, but three interacting helical chains of hydrogen bonds are present in the Pauling-Corey helix, Fig. 6.3. Soliton excitation propagates simultaneously along three chains, and, as Scott [654] showed on a computer model, the excitation energy periodically migrates

between the chains. Thus, the Davydov soliton has internal vibrations with a frequency of about 17 cmÿ1. There are also vibrations
IR range, ÿ 125 cmÿ1, due to the discreteness of the polypeptide chain.

The question of stability of the Davydov soliton under physiological conditions temperature has not been theoretically resolved to date, see page 257. Criticism
The concept of the Davydov soliton is contained in [590], where they prove,
that quantum fluctuations do not allow the Davydov soliton to be
efficient intramolecular energy carrier.

6.7 Fröhlich model of coherent dipole excitations

In the model [441] to describe a quantum system of collective dipole excitations of the medium interacting with a thermostat and with an external EM field, Fröhlich uses the representation of occupation numbers.
Let us first explain the description of a separate quantum oscillator in this representation. The original Hamiltonian of the oscillator has the form

$$H = \frac{P2}{2M} + \frac{M\ddot{y}2x2}{2},$$

where ÿ and M are the natural frequency and mass of the oscillator. If we introduce operator

$$a = \frac{1}{\ddot{y}\sqrt{2}} \; x\,\ddot{y}\sqrt{M\ddot{y}} + i\,\ddot{y}\,\frac{P}{\sqrt{M\ddot{y}}}$$

and use the commutator {x,P} = i, then the Hamiltonian can be written in the form (see, for example, [122])

$$H = \ddot{y}\, a+a + \frac{1}{2}, \qquad (6.31)$$

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where a+ is the Hermitian adjoint operator of a. The term 1/2, representing the zero-point energy, is sometimes omitted when it is irrelevant. The spectrum of eigenvalues of the Hamiltonian is

$$= ÿ\, n + \frac{1}{2} .$$

It is evident that the number n can be considered as the number of excitation quanta ÿ or the occupation number of the state represented by the oscillator, and the operator a+a as the operator of the number of excitation quanta. In the representation of occupation numbers, n is the independent variable. The wave functions of this representation depend on n, the operators act on these numbers. The eigenstates of the Hamiltonian (6.31), denoted, for example, by |n, satisfy the recurrence relations

$$a+ |n = ÿn +1 \overline{|n +1} \,, a |n = ÿn |n ÿ 1 . \qquad (6.32)$$

Therefore, the operators a+ and a are called the creation and annihilation operators of excitation quanta, or the raising and lowering operators. The description of quantum systems in terms of occupation numbers has great generality in many cases and allows the use of algebraic methods to solve problems in quantum mechanics. In this case, the Hamiltonian of the system is not derived, but is written directly in a form similar to (6.31). It is important that for two arbitrarily interacting identical quantum systems described by Hamiltonians proportional to a+a and b+b, the interaction operator can be

represent as an expansion in powers of a, a+, b, b+, with the first term of the expansion of the form ab+ +a+b. Its physical meaning is obvious: exchange of excitation quanta between systems.

A well-known result of condensed matter theory is in that the dynamics of a multiparticle system is described in terms of collective excitations. The complex motion of a multiparticle system can be represented as a superposition of its own collective vibrational modes. Each of these natural vibrations

characterized by the fact that the movement of all particles in the system is ordered and represents a wave. Such are, for example, sound waves in solids.

Fröhlich considered the dynamics of systems of coupled dipoles. Many biophysical constructs such as polyamino acids, membranes, tubulin filaments of the cytoskeleton, etc. are suitable objects modeling using idealized dipole systems. If the system is large enough, then the frequencies of its own collective

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modes form a fairly dense and limited series of frequencies ÿi. By associating each collective mode with an oscillator with the corresponding natural frequency, we can write the Hamiltonian as follows:

systems $\sum_i \ddot{y}_i a_i^+ a_i$. For oscillators of the heat reservoir and the external electromagnetic field with which the dipoles interact, $\ddot{y}_k b_k^+ b_k$ and $\ddot{y}_l p_l^+ p_l$. The write similar Hamiltonians interaction of dipole modes with the thermostat is represented by the sum of the Miltonians of the form

$$\sum_{i,j,k} (a_i b_j^+ b_k + a_i^+ b_j b_k^+) \tag{6.33}$$

And

$$\sum_{i,j,k} (a_i a_j^+ b_k + a_i^+ a_j b_k^+) . \tag{6.34}$$

The first of them describes the process in which one quantum of dipole modes disappears, which is accompanied by the disappearance of the quantum of the thermostat of one mode and the appearance of the quantum of the thermostat of another mode, as well as the inverse process. It is clear that this Hamiltonian contains terms type $a_i b_i^+ + a_i^+ b_i$ as a special case. Due to the law of conservation of energy, $\ddot{y}_i = \ddot{y}_j \ddot{y} \ddot{y}_k$, so the summation is over two indices. The second Hamiltonian takes into account processes involving two quanta.

dipole modes and one thermostat quantum. The remaining possible terms of the interaction operator, corresponding to two-quantum exchange $\ddot{y} a_i a_j$ and $\ddot{y} a_i^+ a_j^+$, as Wu and Austin [727] showed, do not play a noticeable role roles. The interaction of the external source with the dipole modes is, accordingly, proportional to $i(a_i^+ p_i + a_i p_i^+)$.

Using the Hamiltonian H of the system interacting with the thermostat and the external source, that is, the sum of the listed terms, one can find the wave function of the system ÿ(t) and calculate the rate of change of the average number of quanta of the i-th dipole mode $n_i = \langle \ddot{y}(t)|N_i|\ddot{y}(t)\rangle$

$$\dot{N}_i = \frac{i}{\hbar}\langle \{N_i, H\} \rangle, \qquad N_i = a_i^+ a_i ,$$

which was done by Wu and Austin in [726]. Fröhlich obtained the kinetic equation for n_i phenomenologically. Let us show how this can be done.

The intensity (speed) of the process in which, under the action of the operator a_i^+, the occupation number, equal to n, increases by one, is proportional to the square of the matrix element

$$\langle n+1|a_i^+|n\rangle = \ddot{y}\sqrt{n+1} ,$$

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which follows from (6.32), that is, it is proportional to n + 1. Also, for a the velocity is proportional to n. Therefore, if ni, mj are the average occupation numbers of the corresponding dipole modes and thermostat modes, then the rate of change of ni in single-quantum exchange (6.33) is proportional to

$$\dot{n}_i \sim \sum_{j,k} [n_i(m_j + 1)m_k - (n_i + 1)m_j(m_k + 1)] .$$

The minus sign here is due to the fact that the two terms in (6.33) act in in the opposite direction. Using the Planck distribution for the average occupation numbers mj of the thermostat's quantum oscillators

$$m_j = \frac{1}{e^{\omega_j/kT} - 1}$$

and taking into account the law of conservation of energy ωi =ωj + ωk, this expression can be reduced to the form

$$\dot{n}_i = \alpha(\omega_i, T)[n_i e^{\omega_i/kT}(n_i + 1) - n_i(n_i + 1)] , \tag{6.35}$$

where α is a function of absolute temperature and frequency, α = /ωT . Similarly, the rate of change of ni due to two-quantum exchange (6.34) proportional

$$\dot{n}_i \sim \sum_{j} \alpha(\omega_i,\omega_j, T)[n_i(n_j + 1)e^{\omega_i/kT} - (n_i + 1)n_j e^{\omega_j/kT}] , \tag{6.36}$$

where the law of conservation of energy is used in the form ωj + ωi =ωk. The simplification is that the functions α and β are assumed to be constants:

$$\dot{n}_i = s_i + \beta[n_i e^{\omega_i/kT}(n_i + 1) - n_i(n_i + 1)] + \gamma\sum_j [n_i(n_j + 1)e^{\omega_i/kT}(n_i + 1)n_j e^{\omega_j/kT}] , \tag{6.37}$$

where si is the rate of increase of quanta of the i-th mode due to an external source. In the stationary regime $\dot{n} = 0$, the formal solution of this equations for ni are

$$n_i = \frac{c + s_i}{[\gamma + \beta n_j e^{\omega_j/kT} , c = \beta + \gamma n_j e^{\omega_j/kT} , e^{\omega_i/kT}[\beta + \gamma(n_j + 1)] - \gamma c} \tag{6.38}$$

where the summation index is omitted for convenience. Fröhlich gives the following analysis of this expression, which can be rewritten as

$$n_i = 1 + \frac{s_i}{c}\,\frac{1}{e^{(\omega_i/\omega)} - 1} , e^{\omega/\omega} = \frac{\beta + \gamma(n_j + 1)}{c} . \tag{6.39}$$

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From this it is clear that in the absence of pumping, that is, when si = 0, the distribution turns, as it should, into a thermally equilibrium distribution

$$n_i^T = \frac{1}{e^{\gamma_i - \mu} - 1}, \tag{6.40}$$

where ÿ has the meaning of a chemical potential that vanishes at si = 0. If we introduce the excess mi = ni ÿ nT i of the average number of quanta over the equilibrium distribution, then the definition of ÿ takes the form
view

$$\mu + \mu (n_j + 1) \frac{\mu m_j e^{\gamma_j - \mu} - 1 e^{\gamma_i - \mu} = 1+}{\text{It follows that } \mu \mu 0. \text{ On}}. \tag{6.41}$$

the other hand, since the number of quanta is always positive, it follows from (6.39) that ÿ ÿ ÿ0, where ÿ0 is the smallest of the dipole excitation frequency band. Using the definition of ÿ from (6.39), we obtain

$$\frac{s_i}{c} = \frac{s_i e^{\gamma_i - \mu}}{+ \mu (n_j + 1)}.$$

From (6.41) it follows

$$+ 1) = \frac{\mu m_j (e^{\gamma_j - \mu} - 1) \mu + \mu (n_j}{e^{\gamma_i - \mu} - 1},$$

Then

$$\frac{s_i}{c} = \frac{s_i 1 - \mu e^{\gamma_i - \mu} m_j}{(e^{\gamma_j - \mu} - 1) \text{ Now we sum}}.$$

expression (6.37) over i in the stationary mode:

$$S = s_i = \mu \sum_i e^{\gamma_i - \mu} (n_i + 1) = \mu m_i e^{\gamma_i - \mu} - 1, \tag{6.42}$$

where the definition for the excess of quanta mi is used. Together with this equality, we can rewrite the previous expression as follows

$$\frac{s_i}{c} = \frac{s_i}{S} \frac{\mu}{\mu} \quad 1 - \mu e^{\gamma_i - \mu}.$$

Returning to equality (6.39), we can write it in the form

$$n_i = 1+ \quad \frac{s_i}{S} \frac{\mu}{\mu} \quad 1 - \mu e^{\gamma_i - \mu} \quad \frac{1}{e^{(\gamma_i - \mu)} - 1}. \tag{6.43}$$

Summing up the equality ni = nT + mi, we obtain ni = N + NT where N = mi is the total excess of quanta (average) over all states

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their number) over its equilibrium value NT = nT i . Let's sum it up
now (6.43) using the inequalities si <S and ÿ<ÿ0:

$$N + NT\ \ddot{y}\ 1+\ \ddot{y} \qquad \frac{\ddot{y}}{} \quad 1\ \ddot{y}\ e\ddot{y}\ddot{y}\ddot{y}0 \qquad \frac{1}{e\ddot{y}(\ddot{y}i\ddot{y}\ddot{y})\ \ddot{y}\ 1} \cdot \qquad (6.44)$$

From the definition of S (6.42) follows the inequality

$$S = \ddot{y}\ mi \qquad e\ddot{y}\ddot{y}i\ \ddot{y}\ 1 < \ddot{y}N\ e\ddot{y}\ddot{y}max\ \ddot{y}\ 1 \qquad ,$$

that is, with an increase in the pump power S, the average number should increase
quanta N. But, judging by inequality (6.44), this is possible only if
ÿ approaches ÿ0 since 0 ÿ ÿ ÿ ÿ0. Obviously, the population
the lowest state n0 ÿ [eÿ(ÿ0ÿÿ) ÿ 1]ÿ1 increases faster than others.
It gets very big when the pumping is high enough, so
that ÿ ÿ ÿ0. This means that a process similar to Bose condensation is taking place. The
phase transition to a new state in this case is caused not by a decrease in temperature, but
by an increase in the energy flow through the system. The new state is a macroscopic
synchronous oscillation
of all dipole moments with frequency ÿ0 —the so-called coherent excitation.
Fröhlich's analysis of equations (6.38) is a model of the beauty and art of
physical reasoning.

There is a relationship between the Davydov and Fröhlich models.
Tuzhinsky, Paul et al. [632] showed that the original Hamiltonians
both models can be transformed into a common identical form. The equations
of motion for this common Hamiltonian allow, in
in particular, solutions of two types that describe the localization of excitation either in
coordinate space - the Davydov model, or
in the space of quasi-momenta - the Fröhlich model. It is believed that these
effects in complex dipole systems could represent different aspects of the same phenomenon.

6.8 Quantization of the MP flow and effects Josephson

It is known that superconductors are absolutely diamagnetic. The magnetic
field does not penetrate deep into the superconductor. Surface currents are
organized in such a way that they completely compensate for the magnetic field.
inside the superconducting region (Meissner effect). It is also known,
that the charge carriers in a superconductor are pairs of electrons,

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with a charge q = 2e, in the same quantum state. Therefore, the state of a superconductor is described by a single-particle wave function obeying the Schrödinger equation. These idealizations are justified theoretically and in many cases find convincing experimental confirmation [720]. With their help, it is easy to show that

the magnetic flux limited by any superconducting doubly connected region can take only a discrete series of values.

Let the superconductor have an arbitrary shape, for example, a deformed ring, and be placed in a constant external magnetic field H. Let us consider the state of the superconductor inside the ring, where the magnetic field is absent. In this region, H = ÿ×A = 0, that is, the vector potential can be
represent as a gradient of some scalar function w

$$A = \ddot{y}w. \tag{6.45}$$

Let us write the Schrödinger equation for a single-particle state in the magnetic field

$$i\ddot{y}=\ddot{y}\,H\ddot{y} \qquad , \quad H = \frac{1}{2M} P\ddot{y} \left(\frac{q}{c}A\right)^2 + qA0 .$$

The vector potential is defined up to a gauge transformation. The transformation

$$A\ddot{y}\,A = A + \ddot{y}f, \quad A0\ddot{y}\,A \qquad\qquad {}_0 = A0\ddot{y}\ddot{y}f/c , \tag{6.46}$$

where f is a single-valued smooth function of coordinates and time, leaves
observable quantities remain unchanged. The wave function can change only by a phase factor. The Schrödinger equation
is invariant under the simultaneous substitution (6.46) and

$$\ddot{y}\,\ddot{y}\,\ddot{y} = \ddot{y}\exp\left(\frac{IQ}{c}f\right).$$

Indeed, the transformation

$$\ddot{y}\,\ddot{y}A\ddot{y} \qquad , \quad H\ddot{y}\,AHA\ddot{y}1 + iAA\ddot{y}\,\ddot{y}1$$

leaves the equation unchanged. Let the operator A be the phase shift operator A = exp(ÿiÿf), where ÿ is the coefficient, f is a single-valued differentiable function. It is easy to verify that we have
place operator equalities

$$P\ddot{y}\left(\frac{q}{c}A\right)e^{i\ddot{y}f} = e^{i\ddot{y}f}P\ddot{y}\left(\frac{q}{c}A\right), \qquad P\ddot{y}\left(\frac{q}{c}A\right)^2 e^{i\ddot{y}f} = e^{i\ddot{y}f}P\ddot{y}\left(\frac{q}{c}A\right)^2, \quad A = A\ddot{y}\left(\frac{c}{q}\ddot{y}\ddot{y}f\right).$$

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Using these equalities, we find the transformed Hamiltonian:

$$AHAÿ1 + iAAÿ ÿ1 = \frac{1}{2M\,1} eÿiÿf\, P ÿ \left(\frac{q}{c}A\right)^2 eiÿf + qA0 + ÿ ÿf =$$

$$\frac{}{2M}\, P ÿ \left(\frac{q}{c}A\right)^2 + qA_0, A_0 = A0 + \frac{ÿ}{q} ÿf,$$

ÿ = ÿq/c gives the standard form of the gauge transformation (6.46).

By choosing f equal to f = ÿw, we reduce the Hamiltonian to the case A = 0. Therefore, the solution of the Schrödinger equation has the form

$$ÿ=ÿ \exp \frac{IQ}{c} w \;\mathbf{=ÿ|A=0}\; \exp \frac{IQ}{} w \,.\, c \qquad (6.47)$$

Let us now integrate the expression H = ÿ×A over the surface stretched over the contour L passing inside the superconductor, Fig. 6.5, and reduce it to the contour integral, using Stokes' theorem

$$ÿ= ÿ× Ads = Adl = ÿwdl = dw(l)= w. \qquad (6.48)$$

The magnetic flux ÿ is equal to the increment of the function w when going around the circuit L. But due to the single-valuedness of the wave function (6.47) ÿ(l) = ÿ(l + L), where L is the length of the contour, and since w(l + L)= w(l)+ w, it must be

$$\exp \frac{iqw}{c} =1 .$$

That is, wq/c = 2ÿn. Thus, the magnetic flux through the circuit L is equal to an integer number of quanta

$$ÿ0 = 2ÿ \frac{c}{q} = \frac{hc}{2e} =2.0679 \cdot 10ÿ7\ G{\cdot}cm2 .$$

This quantity is sometimes called fluxon or fluxoid.

Josephson [493] showed that when electron pairs tunnel, through a thin insulator or by passing a weak current through a non-superconducting layer between two superconductors, the voltage does not occur at the transition. In this case, the phase jump of the wave function of paired electrons is associated with the magnitude of the current

$$I = I0 \sin ÿ, \qquad (6.49)$$

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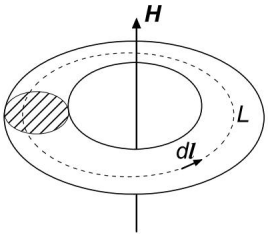


Fig. 6.5: Superconducting ring in MP H. The outline is shown integration of L inside the ring.

what is the essence *of the stationary* Josephson effect. On this
The operation of the so-called SQUIDS, measuring ultra-small MPs, was built.

From expression (6.47) it is clear that the scalar function w coincides with accurate to a factor with a change in the phase of the wave function in the field vector potential inside the superconductor:

$$\ddot{y} = \frac{q}{} w = c \frac{2\ddot{y}}{\ddot{y}0} w. \qquad (6.50)$$

Consider the device shown in Fig. 6.6 - a ring composed of two superconductors separated by two Josephson junctions. The total current I through the SQUID is

$$I = I0(\sin \ddot{y}1 + \sin \ddot{y}2) . \qquad (6.51)$$

On the other hand, the integration of w along the contour L now contains, in addition to the above-considered incursion w = ÿ0n, additional phase shifts ÿ1 and ÿ2, which must be taken with the corresponding bypass
signs. Instead of (6.48), using (6.50), we write:

$$\frac{\ddot{y}0}{2\ddot{y}} (\ddot{y}2 \ddot{y}\ddot{y}1) , \ddot{y}=\ddot{y}0n + \quad \text{or } \ddot{y}2 \ddot{y}\ddot{y}1 =2\ddot{y} \ddot{y} 2\ddot{y}n. \quad \frac{\ddot{y}}{\ddot{y}0}$$

Applying this to expression (6.51), we find that the current in the ring oscillates with the change in magnetic flux through the ring:

$$I \ddot{y} \cos \ddot{y} \ddot{y}0 \quad \frac{\ddot{y}}{} \ \ddot{y} \ddot{y}n .$$

The distance between adjacent maxima of this function is equal to 2ÿ0,
which for a ring with an area of 1 cm2 determines the MP H ÿ 4 10ÿ7 G. The accuracy of measuring the position of the maxima is usually of the order of 1–0.1%,

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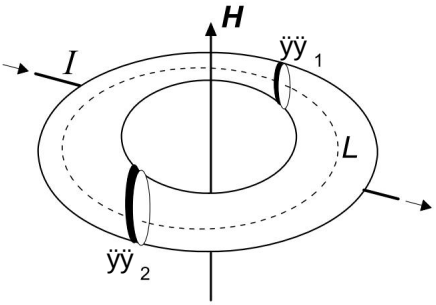


Fig. 6.6: Squid in MP H.
At Josephson junctions
wave phase jumps occur
functions of superconducting electrons
thrones ÿ1 and ÿ2.

for this, the minimum detectable MP is about 10ÿ9 Gs or
10ÿ13 Tl.2

If the current I in (6.49) exceeds the critical value I0, then a voltage arises at the contact; this mode is called *the transient* Josephson effect. With a fixed potential difference at the contact V, the phase difference and the current oscillate with a frequency ÿ =

2eV/. Passing through the contact, a pair of electrons loses energy ÿ =
2 eV, which is emitted as electromagnetic field quanta. The radiation frequency falls into the microwave range at laboratory voltages; at 1 mV, the frequency is 483.6 GHz.

The phenomena considered are largely due to the fact that
The magnetic field does not penetrate deep into the superconductor and, therefore, the vector we represent the potential as the gradient of some function A = ÿw
(6.45). Interesting phase effects followed from this. There is another phenomenon not related to superconductivity, the effect
Aharonov–Bohm [242], in which unusual phase relations
are determined by the gradient representation of the vector potential. The Aharonov–Bohm effect is that the parameters of motion of a charged quantum particle depend on the magnitude of the magnetic field in the region where the particle itself
the particle cannot be located. At first glance, this seems paradoxical.
greasy.

Let us consider the states of a quantum particle in the region around a long solenoid with magnetic flux ÿ. A convenient idealization is that the solenoid is infinitely long and infinitely thin. The first ensures that the magnetic field outside the solenoid is zero, the second ensures that the probability of the particle being inside the solenoid is zero, where the magnetic field
exists. If the solenoid is directed along the z-axis, then the vector potential

2The sensitivity of SQUID magnetometers to magnetic fields reaches 10ÿ10 G Hzÿ1/2.

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potential has only a ÿ-component, since H = ÿ× A. And since

A dl = Aÿ 2ÿr =ÿ, then for a finite flow ÿ the vector potential equal

$$A\ddot{y} = \frac{\ddot{y}}{2\ddot{y}r}$$

everywhere except the point r = 0. Let the motion of the particle be limited by a contour enclosing the solenoid, for example, a circle of radius r. Then the Hamiltonian of the particle reduces to

$$H = \ddot{y}0\ \ddot{y}i\ \ddot{y}\ddot{y} \quad \frac{\ddot{y}}{} - \frac{\ddot{y}}{\ddot{y}0}^{2}, \ddot{y}0 = \frac{2}{2Mr2}.$$

The eigenfunctions of the Hamiltonian ÿ exp(imÿ), the eigenvalues of the projection of the momentum operator onto the trajectory of motion are m = 0, ±1, .. , and therefore the energy spectrum is

$$\ddot{y} = \ddot{y}0\ m\ \ddot{y} \quad \frac{\ddot{y}}{\ddot{y}0}^{2}.$$

As can be seen, the spectrum depends on the magnetic flux inside the solenoid. If the solenoid passes outside the particle's motion contour, then ÿ = 0 and the spectrum takes the form typical for a rotator: ÿ ÿ m2.

Such a dependence is not a consequence of excessive idealization of an infinitely long and thin solenoid and is of a general nature (see, for example, the review by Skarzhinsky [178]). The question of how a particle “feels” the magnetic field where it does not appear has given rise to many metaphysical publications. Essentially, it was discussed whether the potentials of the electromagnetic field are primary, in comparison

with electric and magnetic fields, reality. Due to the gauge invariance of the dynamic equations for observable physical quantities, the potentials themselves are not observable. However, gauge-invariant quantities associated with potentials are. These are 1) local quantities—the strengths of EM fields (derivatives of potentials) and 2) nonlocal quantities—the integrals of potentials over closed trajectories; they depend on the spatiotemporal distribution of EM fields. The first quantities determine the local force effects on a particle,

the second are non-local non-force effects specific to quantum mechanics. The reality of non-local interactions is

reflected in the so-called paradoxes of quantum mechanics, for example, in the Einstein-Podolsky-Rosen paradox. One of the striking manifestations

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nonlocal interactions are experiments on the so-called quantum
teleportation [684, 701].

The special role of vector potential in magnetobiology was discussed by Trukhanov [192]. An experiment was proposed to observe the effect
Aharonov-Bohm through a biological system encompassing
a toroidal solenoid with a magnetic field inside. Note that, from an orthodox point of view, the effect of the vector potential of a solenoid on a biological system is plausible only if

The EMF target quantum system encompasses the magnetic flux of the solenoid, that is, it is macroscopic. Throughout this book, only localized microscopic quantum targets have been considered.
MP. The existence of macroscopic single-particle quantum states in biological systems at physiological temperatures is practically improbable. This brings us back to the poorly substantiated idea of the so-called
biological superconductivity. At the same time, there are experiments indicating long-range intercellular communication. It is possible that it could be described in terms of

single-particle quantum state. Therefore, the one proposed in [192]
The experiment is still not without heuristic value.

A simpler experiment to identify the role of vector potential is based on the use of exposure of a biological system to

inhomogeneous magnetic field, for example, in the field of a ring with current. By choosing a contour integration of A infinite and including the ring axis, it is easy to see that A = 0 everywhere on the ring axis. At the same time, the MP on the ring axis
radius R with current I equals 3

$$H = \frac{2\ddot{y}IR2}{3/2_{c'}(R2 + h2)}$$

where h is the distance from the plane of the ring. Thus, if the experiment shows a specific dependence of the MBE on h, this indicates
that it is precisely the heterogeneity of the vector potential (that is, the MP),
and not its absolute value, is detected by the biological system.
Similar experiments are known: Blackman, Blanchard, and others in [421], de Séze, Taffet et al. [393] placed organisms in different areas on the axis of solenoidal exposure systems and observed changes in biological effects. At the same time, such experiments do not prove that
the absolute value of the vector potential cannot manifest itself there,
where it is different from zero [265].

3A point magnetic moment ÿ creates a vector at a distance r in the direction **n** potential **A** = (ÿ × n)/r2 and MP [3n (ÿ n) ÿÿ]/r3.

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Literature

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