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On the physical nature of magnetobiological effects

V.A. Milyaev, V.N. Binhi

***Abstract*. The problems of the theory of so-called nonthermal biological effects of electromagnetic fields are considered. It is shown that these effects can be described by the interaction of electromagnetic fields with the quantum states of molecular biophysical structures and subcellular systems.**

Keywords: *biological effects of electromagnetic fields, magnetoreception, theoretical models, magnetosome, interference of quantum states, stochastic resonance.*

1. Introduction

Alexander Mikhailovich Prokhorov, who actively supported studies in the field of magnetobiology, pointed out in his preface to monograph [1]: 'It is safe to say that a new field, magnetobiology, has made its appearance in theoretical biophysics. The field still continues to cause much discussion, but it calls for more sophisticated studies to be caried out using rigorous mathematical and physical tools'. In this paper, we present a brief review of theoretical magnetobiological studies performed by now at A.M. Prokhorov General Physics Institute, RAS.

Today, the extensive experimental data have been accumulated on nonthermal (i.e. without heating) biological effects produced upon low-intensity laser irradiation [2 – 4] and action of weak low-frequency and radio-frequency electromagnetic fields [5 – 8]. In the latter case, the nonthermal nature of effects follows from the fact that (i) the intensity of acting electromagnetic fields (EMFs) is by no means sufficient for any noticeably heating of a biological tissue; the responses of the biological system to EMFs and heating are sometimes opposite, and (ii) these effects take place only in some EMF frequency intervals. In the literature such effects are called magnetobiological effects (MBEs). Also, biological effects are observed which appear only in some intervals of the field amplitude. This contradicts to the concept about the exclusive thermal origin of MBEs on which most of the electromagnetic safety standards are based.

V.A. Milyaev, V.N. Binhi A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; e-mail: kvant@biomag.info, milaev@kapella.gpi.ru

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Note that the nature of biological effects of laser radiation is also not completely understood [9 – 11]. Are there any common features in the physical nature of biological effects of EMFs in such different frequency ranges as optical, microwave, and low-frequency? It seems that it is impossible to answer unambiguously this question. On the one hand, there are reasons to assume that low-frequency and radio-frequency EMFs act on the same targets in biological tissues, but on the other hand it has been found that combined radiations, monochromatic laser radiation and relatively broadband LED radiation, produce a specific therapeutic action. In this case, the emission spectra contain obviously the microwave component as well. It is not inconceivable that some targets can response both to laser and EMF radiation.

In experiments performed at the same laboratory, a particular MBE is reliably reproducible, as a rule. However, many MBEs have not been confirmed so far by experiments performed at different independent laboratories. There exists an important exception: an MBE on melatonin – a hormone regulating the carcinogenic resistance of organism, was observed at five from ten independent scientific groups [12, 13]. A poor reproducibility of the results is explained by different 'electromagnetic' conditions of the experiments in which the important parameters are not only the frequency and amplitude of alternating EMFs but also the strength of permanent magnetic and electric fields and their orientation. Small variations in the genotype of a biological species also can determine the magnitude of the effect [14]. That is why the experimental observation of MBEs has so far the probabilistic nature in a certain sense.

Investigations performed for many years have shown that background electromagnetic fields are no less important biotropic factor than temperature, pressure, and humidity and have a hidden type of action. It is assumed that the results of uncontrolled exposure to EMFs can appear after several months or even years.

These facts gave rise to the so-called precautionary principle of the World Health Organisation prescribing the reduction of the exposure of people to electromagnetic radiation even in when the nature of possible biological effects of weak EMFs is unknown.

Many foreign electromagnetic safety standards neglect the possibility of nonthermal effects. Note that standards accepted in different countries differ from each other by hundreds and more times, which suggests that they are poorly substantiated.

The development of better standards requires the explanation of the physical nature of nonthermal effects

produced by EMFs. At present the commonly accepted explanation of MBEs is absent. Moreover, some physicists assume that such an explanation is impossible at all because of the so-called κT problem, while the observation of MBEs contradicts to physical laws and, therefore, is an artefact.

Experiments containing information on the physical processes of magnetoreception were analysed in monograph [1]. The experiments reveal a certain generality in the manifestations of MBEs observed for a variety of biological objects at different laboratories under various experimental conditions. These common elements or facts provide a basis for the theoretical generalisation [15]. Each of the facts presented below excludes physically unacceptable MBE mechanisms, thereby restricting the scope of the search for acceptable mechanisms.

(i) The incompatibility of the energy scales of magnetic fields (MFs) and biochemical reactions caused by MFs. This circumstance is usually is formulated as the 'κT problem' or 'κT paradox': if the energy quantum of a weak low-frequency MF is many orders of magnitude lower than the characteristic energy $\epsilon_{\text{chem}} \sim \kappa T$ of a single event of chemical transformations, then how the reaction can occur? Note that such a reasoning in incorrect because in the low-frequency region even a very weak MF is a classical field with a large margin and the applicability of the concept of a quantum of such a field is restricted [16]. But even the treatment of an EMF as a classical field does not eliminate the paradox. This paradox is also related to the fact that, according to a widely accepted opinion, a charge or an ion involved in a chemical reaction should have the energy sufficient for overcoming the energy barrier of the reaction. This energy is usually imparted by surrounding particles involved in the thermal motion, and the contribution of a weak MF is negligible in this case. We can estimate the time needed for the transfer of the low-frequency MF energy to an ion required for initiating the chemical process. Under ideal conditions, when the ion is a part of an oscillator (and only in this case it can accumulate the energy) and there is no damping or friction, this time amounts to about a year even in the resonance case, when the rate of energy transfer between the MF and oscillator drastically increases. Therefore, the primary physical mechanism responsible for magnetoreception cannot be resonant. Note also that the most efficient MF configuration is a combination of parallel permanent and alternating MFs [17], which also suggests that MBEs have the nonresonance nature: magnetic resonance can be excited only in an alternating MF perpendicular to a permanent field.

(ii) The observation of the frequency action spectrum of a MF in some biological systems (see, for example, [14, 18]). It has been found that the effective MBE frequencies coincided with the cyclotron frequencies of biologically important Ca, Mg, and other ions in the geomagnetic field [19]. In addition, the effective frequencies were proportional to the magnetic field strength, the positions of spectral bands being described by the relation qH/Mc, where q and M are the ion charge and mass, respectively; H is the permanent MF strength, and c is the speed of light. Macroscopic charged objects with the charge-to-mass ratio as for calcium, magnesium, and other ions are unknown. This means that in the case of frequency-selective MBEs, a weak (the magnetic field induction B is lower than 100 μT) low-frequency (< 1 kHz) MF acts on targets of the atomic-molecular scale in biological tissues. At the same time, we cannot state that the cyclotron resonance is the primary MBE mechanism: any mechanism involving ions moving in a MF will deal with cyclotron frequencies because there are no other combinations of the ion and MF parameters. The second conclusion concerns the involvement of the Zeeman effect, i.e. a linear dependence of the energy of the stationary motion of a charge on the MF strength. In this case, the moving particle should have the magnetic, orbital or spin moment.

(iii) The observation of the MBE nonlinearity [20, 21]. As the magnetic field amplitude increases, the MBE first increases and then decreases. In addition, two and three maxima of the amplitude dependence were observed [22], as well as even more complicated amplitude spectra [23]. The nonlinear character of the MBE is also manifested in the fact that the biological response to a sum of electromagnetic stimuli is not equal to the sum of responses to each individual stimulus. In particular, the MBE can be destroyed by adding a magnetic noise to the exposure field. Such effects are impossible in linear systems. It may seem that the presence of the efficient frequencies or the frequency spectrum points to the resonance action of the MF on a primary target. However, the MBE nonlinearity refutes this conclusion. In the case of a low excitation level, the resonance, i.e. an increase in the energy transfer rate in the system upon coincidence of the excitation frequency with the eigenfrequency of the oscillator is a linear effect. The only possible nonlinearity can appear in this case due to the saturation of the resonance in comparatively strong fields but not due to its violation, while the known nonlinear resonance cannot be observed under the excitation conditions used in MBE experiments. The measured amplitude dependences of the MBE behave as functions of the Bessel type, which suggests that general physical principles are involved in the magnetoreception process. Thus, the primary physical mechanism of the MBE is hardly related to resonance processes also due to the MBE nonlinearity.

(iv) The similarity of biological effects of weak low-frequency magnetic and microwave fields. Effects of both types have been repeatedly observed in the same biological systems. In particular, modulated microwaves exhibit the resonance dependences on the modulation frequency, the effective frequencies being coincident with those observed in the effects produced by low-frequency MFs. This points to the common molecular physical nature of the biological action of low-frequency MFs and microwaves. Note also that the biological effect considerably depends on the polarisation of microwaves [24], which is well known for EMFs interacting with molecular systems having the intrinsic magnetic moment.

(v) The observation (sometimes) of biological effects of EMFs which have the opposite 'direction' compared to thermal effects. This also points to the nonthermal nature of these effects.

(vi) The observation of biological effects correlating with slow variations in the geomagnetic field. Such fields should be treated as quasistatic because biophysical structures have no objects with such low frequencies. There are good reasons to believe that variations in a permanent MF corresponding to geomagnetic variations can directly affect biological systems [25].

These are the basic facts. Their combination is sufficiently unique for making the following conclusions: (i) the primary processes, which are not related to the frequency

selectivity, should involve intermediate submicron structures having the intrinsic magnetic moment whose energy in a weak MF exceeds noticeably κT; and (ii) the primary resonance-like processes involved in the response of biological systems to weak EMFs develop at the atomic-molecular level and are related to the Zeeman effect, but are not resonant.

Below, we consider physical processes that can be responsible for the appearance of magnetobiological effects.

1.1 Interaction of a MF with the magnetic moment

Submicron particles with the magnetic moment have been found in many living objects. The magnetic moment μ of magnetite particles exceeds the elementary moment by 7–9 orders of magnitude. Their rotation energy in a weak magnetic field H considerably exceeds the energy κT of thermal fluctuations. For single-domain magnetite particles of radius 100 nm in the geomagnetic field, $\mu H = \upsilon J H \approx 24\,\kappa T$ (υ and J are the volume and saturation magnetisation, respectively). The intrinsic MF of a particle in its vicinity achieves 0.2 T (this is more than three orders of magnitude higher than the geomagnetic field) and strongly depends on its orientation, so that the rotation of the particle can noticeably change the rate of chemical reactions involving free radicals.

Of special interest are magnetite particles found in the brain of many animals and human beings, which are assumed responsible for one of the mechanisms of action of weak MFs on organisms (see, for example, review [25]). It was found that these particles have the biogenic origin, i.e. they are formed due to prolonged crystallisation directly in the brain. Biogenic magnetite particles are often called magnetosomes. The magnetosome density in the brain tissue of human beings is no less than 5×10^6, and it exceeds 10^8 crystals per gram in pia [26], or is 50 ng g^{-1} on the average [27].

The magnetosome energy in the geomagnetic field is about 24 κT, and therefore, regular variations in this energy in an additional alternating magnetic field h are about $(h/H_{geo})24\,\kappa T$. If these regular variations exceed random variations of the order of $\kappa T/2$, they can cause a biological reaction. This circumstance restricts the strength of an alternating MF capable to affect a biophysical or biochemical system by the relation $h \gtrsim 1$–2 μT. However, as shown below, the limiting value of the MF detected at the biological level can be an order of magnitude lower under the conditions of nonlinear stochastic dynamics of magnetosomes moving in a potential of the general form with two minima. Then, in a number of cases thermal perturbations do not mask but, on the contrary, favours the manifestation of weak magnetic forces.

1.2 Interaction of a MF with a moving charge

All physical processes in which EMFs affect the motion of a charge can be divided into classes according to the type of description of the charge dynamics (classical or quantum-mechanical) and according to the type of a dynamic variable whose value considerably changes during the interaction with EMF. The state of a particle in classical dynamics is specified by its coordinates and velocities, and in the quantum-mechanical dynamics – by the wave function or the density matrix. The dynamic variables are coordinates of a particle, its momentum (or angular momentum or energy) and a spin ('internal' variable).

The processes presented in Table 1 can be readily commented from the point of view of their involvement in magnetoreception.

Table 1. Classes of transformation processes of MF variations to changes in the variables of a particle motion.

Object of the MF action (variables)	Charge dynamics	
	Classical	Quantum-mechanical
Coordinate	Motion under the action of the Lorentz force	Interference of states
Energy (momentum, angular momentum)	Energy pumping	Quantum transitions
Spin	–	Spin dynamics

A change in the energy of a particle in the MF was discussed above. It was pointed out that a sufficient energy cannot be accumulated during reasonable time intervals even under ideal resonance conditions, and the accumulated energy does not correspond to the observed nonlinear magnetoreception of weak fields. This conclusion is independent of whether the description method is classical or quantum-mechanical.

The spin dynamics could be manifested in reactions involving pairs of free radicals [28]. It is known that the spin selection rules in the magnetochemistry of radical pairs do not require the accumulation of the MF energy in the spin degrees of freedom. However, there exist a number of physicochemical factors restricting a change in the rate of radical reactions by the value not exceeding 1 % per 1 mT. This is not sufficient for a reliable explanation of biological effects of weak alternating MFs with the amplitude of the order of 50 μT and lower. In addition, this mechanism is not frequency-selective.

The action of a MF on the coordinates of a particle can be described both classically and quantum-mechanically. In the classical dynamics, a particle moving in the MF is subjected to the action of the Lorentz force, which is perpendicular to the velocity vector. The particle is deflected from a linear trajectory, but this deflection during the free-path travel time in a medium is extremely small, being billion times smaller than the mean free path. Obviously, this process has no relation to magnetoreception.

There remains only the MF action on the coordinates of a quantum-mechanical particle, more exactly on the coordinate probability distribution, i.e. on the wave function of the particle. The redistribution of the wave-function density in the MF does not require the accumulation of energy corresponding to a single event of the chemical reaction because it occurs due to the phase shift of the wave-function components. At the same time, the redistribution in the wave-function density is caused by nonlinear interference effects, which can affect the development of the chemical process. The explanation of MBEs by such processes was first proposed in [29].

Weak microwave and low-frequency EMFs cannot produce the dissociation of chemical bonds in biological molecules. However, EMFs can control the dissociation of molecules caused by some other reasons. During metabolism, many ions and small molecules bind to proteins, thereby changing their biochemical activity. The inverse dissociation process also occurs. Both processes are involved in the formation of biological equilibrium. An alternating

EMF with special parameters can shift the equilibrium due to the interference of the ion–molecular quantum states, thereby producing biological effects. Note that the physical nature of interference is not related to the heating of biological tissues caused by the EMF energy absorption. Therefore, it can occur even in very weak EMFs which cannot cause heating.

It is important that not only the frequency and amplitude of the alternating EMF strength but also the strength of a permanent MF are important parameters. The dissociation probability for the fixed frequency and amplitude depends on the local MF strength, which is one of the reasons for a poor reproducibility of MBEs.

The theory of interference of quantum angular ion–molecular states allows one to calculate the spectra of dependences of MBEs on any parameters of electromagnetic exposure [6]. A comparison of theoretical and experimental spectra has shown their good agreement. Such an agreement is quite unusual for comparison of the physical theory with biological experiments.

2. Some of the proposed models

One of the first ideas in the field of magnetobiology is related to the so-called biogenic magnetite in a magnetic field. In tissues of some animals and in microorganisms, microscopic magnetite crystals capable of magnetisation are formed. Upon the interaction of these crystals with an external MF, a torque is formed, and crystals exert pressure on surrounding tissues, thereby initiating a chemical reaction [30]. However, this mechanism can explain only some of the magnetobiological effects because unicellular organisms, which do not contain magnetite, also can response to a magnetic field. In many cases, the reaction has a complicated nonlinear, often multipeak (depending on the field parameters) character. It is also necessary to explain the response to variations in the MF that are lower than the natural limit determined by the energy of particles of biogenic magnetite in the geomagnetic field.

Orientation effects can also appear at the molecular level as manifestations of dia- and paramagnetism. However, they become considerable only in strong enough MFs, of the order of 1 T and above.

The biological efficiency of weak MFs is explained sometimes by representing biological tissues or biological structures in the form of equivalent distributed electric circuits. In any case, such a phenomenological approach does not solve magnetobiological problems.

The hypothesis that eddy electric currents induced by a low-frequency MF in biological tissues cause magnetobiological effects has been verified in many experiments. These currents can heat the biological tissue and shift electrochemical reactions if their density exceeds the density of natural biocurrents (~ 1 mA m^{-2}). The currents are determined by the induced electric field strength, which is proportional to the product of the field strength amplitude and the MF frequency. If the hypothesis is correct, the MBE should correlate with variations in this quantity. Indeed, such a correlation was observed in some experiments with increasing the alternating MF strength. However, no correlations were observed in several independent experiments with relatively weak MFs of the order of the geomagnetic field. This suggests that there exist the primary MBE mechanisms that are not related to eddy currents.

It is often said that the action of weak physicochemical factors on biological systems has the information or signal character. In this case, it is assumed a biological system is in a state that is close to the unstable dynamic equilibrium. Therefore, it is sufficient only to push the system and it will undergo a transition to another state due to its internal resources. In other words, the so-called biological amplification of a weak MF signal will occur. This process can be described phenomenologically by the equations of chemical kinetics. Under certain conditions, the solutions of these equations reveal bifurcations – the transition to a qualitatively different dynamic regime under the action of a weak perturbation. The application of this approach to electromagnetobiology was discussed, for example, in [31, 32].

The important question arises: Why thermal fluctuations at the energy scale exceeding the energy quantum of the magnetic field by ten orders of magnitude do not destroy the MBE? It is assumed that it can be explained by the coherent action of an external factor against the background incoherent thermal noise. In this case, a high-Q oscillator can be excited to a state (temporal coherence) in which its energy will be sufficient to initiate a chemical reaction or to change the synchronous system of oscillators (spatial coherence) so that to obtain an energy quantum of collective excitation [33, 34].

Another explanation is based on the assumption that not the oscillator energy but some other parameters of the oscillator, for example, polarisation of vibrations acquire properties under the MF action which affect the operation of biophysical systems related to the oscillator. Thus, the application of the Larmor theorem to an ion bound in a calmodulin microcavity was discussed in [35, 36]. The central idea was that the direction of ion oscillations exerts a decisive effect on the protein shape, which in turn causes a change in the enzyme activity. The change in the direction of oscillations in alternating MFs of different configurations was studied within the framework of classical dynamics. However, the authors of [35, 36] failed to explain completely the experimental data.

Yet another idea proposed to explain the overcoming of the thermal factor is based on the use of the so-called stochastic resonance to solve the 'κT problem' [37]. However, the gains obtained in real systems did not exceed 100 [38], which is far from being sufficient to explain the biological activity of weak low-frequency MFs based on molecular mechanisms. It was recently found [39–42] that magnetic nanoparticles in a cytoskeleton can be in a stochastic resonance. These models are promising for explaining the biological activity of slow variations in the geomagnetic field, 'magnetic vacuum', and biological orientation in MFs.

The resonance-like character of biological effects produced by EMFs is observed both in the low-frequency and radio-frequency ranges. To explain these effects, several mechanisms were proposed, in particular, including a change in the conformation of proteins caused by the EMF induced change in the hydration degree of some molecules [43].

The dependences of some magnetobiological effects on the MF modulation frequency and amplitude exhibit the high-efficiency bands. The dependences of MBEs on the MF parameters can give information on the primary magnetoreception mechanisms. These dependences were explained by using the mechanisms of transformation of the MF signal

at the microscopic dynamic level and classical and quantum-mechanical models of binding of some ions by proteins [44, 45]. The biological activity of protein depends on the presence of the corresponding ion in a bound state. It was assumed in [46] that the EMF can change the binding constant (the so-called calmodulin hypothesis). In [45], it was found that the amplitude dependences of some MBEs were similar to these dependences for parametric resonance in atomic spectroscopy [47] studying the parameters of quantum transitions. This model, called the 'parametric resonance of ions', initiated a number of papers, which however failed to explain this similarity.

The interference of quantum states known in physics was used to explain the physical nature of magnetoreception [29]. A MF varied over its magnitude but not direction changes only phases of the wave functions of a charged particle. It is interference that relates variations in the phases of wave functions with observed quantities. The interference of quantum states in atomic spectroscopy is related to coherent quantum transitions in an atom rather than to the internal structure of the wave functions of electrons. At the same time, it is the latter that determines the interference of ions in an ideal cavity in an alternating MF in the absence of quantum transitions.

The biological action of a device providing a closed magnetic flux of a considerable magnitude was observed in [48]. It was found that the MF of strength equal to that of the stray magentic field of the device did not produce any effects. The authors substantiated the possible role of the vector potential of the EMF acting on various objects. The obtained experimental results were explained as the macroscopic effect of the vector potential field.

Many authors explain the biological action of MFs by a change in the water state induced by external fields, which affects biological processes caused by the participation of water in various metabolic reactions. It is not clear at present what namely MFs can affect in water. Stable water-molecular associates possessing the memory to the electromagnetic action were discussed based on the study of low-frequency electric-conductivity spectra of water in [49]. Stable structural variations in water were observed by luminescence spectra [50]. They were explained by the presence of various defects in water with characteristic emission centres.

In recent years a model is being developed in which water is treated as a 'knit' structure of linear molecular associates or strips composed of approximately 20 oriented water molecules [51]. The state of such a system is described by rotational soliton excitations propagating along the strips and interacting with excitations on adjacent strips and with the external EMF.

The nature of memory carriers in water and their interaction with EMFs are not clear at present.

It is most likely that elementary targets in a water matrix are the magnetic moments of protons in hydrogen bonds. A simultaneous matched action on magnetic moments and, therefore, on the spin states of protons can affect the spin selection rules in rearrangements of hydrogen bonds, thereby changing the state of conformational mobility of proteins [1, 16, 52].

Consider in more detail the mechanisms that are, in our opinion, most promising for the explanation of magneto-biological phenomena.

3. Dynamics of magnetosomes in a cytoskeleton

3.1 Stochastic resonance of magnetosomes

The motion of a considerable part of magnetosomes attached to a cellular membrane with cytoskeleton filaments occurs mainly in a double-well effective potential. The two or more stable equilibrium positions appear due to competition between mechanical and magnetic forces.

We will show that in alternating magnetic fields with the amplitude 5–10 μT, the regular rotations of particles by the angle ±1 rad (rather than 0.14 rad, as in the case of free rotations) appear against the background of a permanent MF, which substantially facilitates the interpretation of magnetobiological effects. Such a regime exists in the range of the permanent MF of the order of the geomagnetic field, which is limited from both sides.

Let us use the Langevin equation for rotational vibrations of a particle in a plane formed by the unit vector $\boldsymbol{n}$ of the x axis, with which the magnetic moment vector of a magnetosome in the absence of a MF coincides (the equilibrium position $\varphi = 0$), and the MF strength vector $\boldsymbol{H}$ (Fig. 1):

$$I\ddot{\varphi} + \gamma\dot{\varphi} + k\varphi = -\mu H(t)\sin(\varphi - \varphi_0) + \xi'(t),$$

$$\omega_0 = (k/I)^{1/2},$$

where φ is the angle of rotation of a particle; I is the inertia moment of a particle; γ is the damping coefficient; k is the elastic coefficient in bending of cytoskeleton filaments; $\xi'(t)$ is the random mechanical moment with the correlation function $\langle\xi'(t)\xi'(t+\Delta t)\rangle = 2\gamma\kappa T\delta(\Delta t)$; ω_0 is the vibrational eigenfrequency; and the angle φ_0 specifies the MF direction.

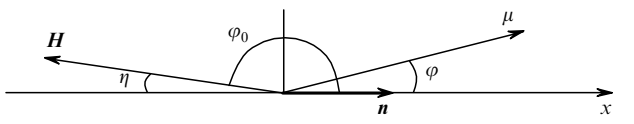

Figure 1. Mutual arrangement of the magnetic-field vector and the magnetic moment vector of a magnetosome.

Of interest is the dynamics of magnetosomes oriented predominantly opposite to the direction of a permanent MF ($\varphi_0 = \pi$). The potential energy of a magnetosome for $a = k/\mu H < 1$ (a is the elastic parameter of the bond) has two stable equilibrium positions ($\varphi_\pm$) and one unstable position ($\varphi = 0$).

Due to thermal perturbations, transitions from one well to another occur even in the absence of an alternating MF. In this case, a particle experiences random rotations by large angles. A regular external force, an alternating MF in our case, introduces ordering in these transitions, the degree of this ordering achieving maximum at a certain optimal noise level. This is the known effect of the so-called stochastic resonance. In the presence of the variable MF component $h\sin(\Omega t)$, the equation is reduced to the form which is standard for the stochastic resonance theory:

$$\dot{\varphi} + \partial_\varphi U(\varphi, \tau) = \sqrt{D}\xi(\tau),$$
$$U(\varphi, \tau) = \cos\varphi + \frac{a}{2}\varphi^2 - \varphi h'\sin(\beta\tau). \qquad (1)$$

Here, $\xi(\tau)$ is the centred Gaussian process with the unit dispersion; $h' = h/H$; $D = 2\kappa T/\mu H$; $\tau = \mu H t/\gamma$; and $\beta = \gamma\Omega/\mu H$.

Upon the action of a MF on the interwell transitions of a magnetosome, the signal-to-noise ratio for the angle of rotation φ is described by the expression [40]

$$R_{\rm sn} \approx \frac{6\sqrt{2}\,h'^2(1-a)^2}{D^2}\exp\left[\frac{-3(1-a)^2}{D}\right].$$

Let us find the limiting sensitivity of a detector of a weak MF based on the magnetosome dynamics from the equation $R_{\rm sn} = 1$, which determines the implicit dependence of the MF amplitude h' on the elastic parameter. Figure 2 shows the dependence for magnetosomes of different sizes. One can see that there exists a considerable interval of the elastic parameter $a = k/\mu H$ in which the signal-to-noise ratio is equal to unity for weak MFs. The standard magnetosome of radius 100 nm fixed in a cytoskeleton with the elastic coefficient $k = (0.7-0.9)\mu H$ executes in an alternating MF of strength 10–13 μT and in the geomagnetic field of strength 46 μT regular rotations through the same angles as during random rotations (about 2 rad). Upon regular rotations through such angles, the relation between the rotation of magnetosomes and biochemical processes becomes especially obvious. There exists the efficiency 'window' over a permanent MF. As the MF decreases, the potential becomes single-well, while with increasing the MF, a potential barrier increases and a magnetosome remains in one of the wells, which also excludes the manifestation of a stochastic resonance.

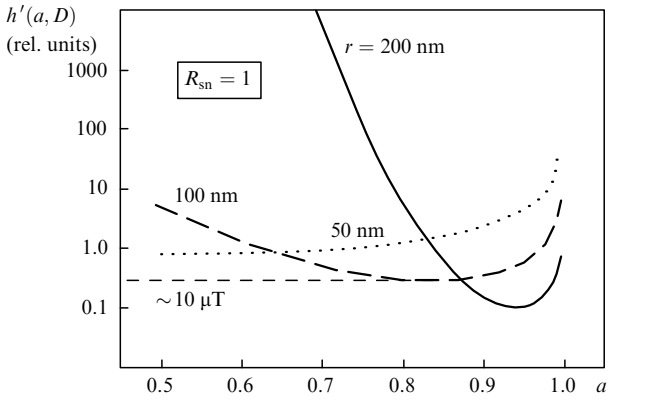

Figure 2. Maximum sensitivity of magnetosomes of different sizes to the alternating MF. The 10-μT level is calculated for $H = H_{\rm geo}$.

Thus, the stochastic resonance of magnetosomes can explain the biological action of relatively weak low-frequency MFs against the permanent MF background comparable with the geomagnetic field.

3.2 Dynamics of magnetosomes upon variations in the geomagnetic field

A part of magnetosomes make random turns through a large angle even in the absence of an alternating MF. If magnetosomes exert some averaged influence on a biochemical reaction, the reaction rate is sensitive to the 'magnetic vacuum' conditions $h \ll H \ll H_{\rm geo}$. Moreover, the reaction is also sensitive to small variations in a permanent MF because the probability W of transitions between wells exponentially depends on the barrier height U_0. In [38], this probability is defined as

$$W = \frac{1}{2\pi}\left[|U''(0)|U''(\varphi_\pm)\right]^{1/2}\exp(-2U_0/D),$$

where U'' is the potential curvature at the equilibrium points. All the quantities here are functions of the elastic parameter $a = k/\mu H$ and, hence, of H. The relative change in the probability upon small variations in the permanent MF strength determines the sensitivity S of this probability to variations in the MF strength:

$$S = -\frac{1}{W}\frac{{\rm d}W}{{\rm d}(H/H_{\rm geo})}.$$

Figure 3 presents the sensitivity S calculated for different elastic parameters of binding between the average magnetosome and cytoskeleton. In a rather broad range of the elastic parameter the sensitivity of the relative probability to variations in the MF strength near $H_{\rm geo}$ is 10–20, i.e. variations in the geomagnetic field strength by 1 % cause changes in the transition probability by 10 %–20 %. This gives the limit of detectable variations in a permanent MF equal to $\sim 0.005H_{\rm geo}$, or 200 nT. The operation in such a regime does not exclude the possibility of the response of a biological system containing magnetosomes to slow geomagnetic fluctuations.

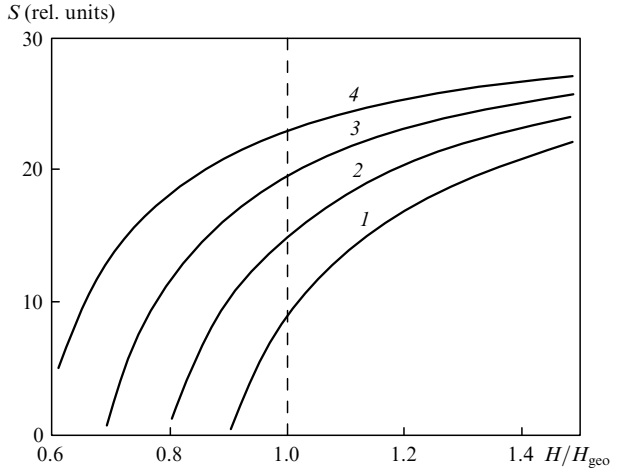

Figure 3. Sensitivity S of the transition probability to variations in the MF strength for $k/(\mu H_{\rm geo}) = 0.8$ (*1*), 0.7 (*2*), 0.6 (*3*), and 0.5 (*4*).

Therefore, there exists a peculiar amplification mechanism: slow (1 %) variations in the geomagnetic field (those of the geomagnetic storm level 100–200 nT) change the average lifetime of particles in different states by 10 %–20 %, which causes the same variations in the local average MF near magnetosomes. Because the local field near magnetosomes is tens of millitesla, the 'gain' achieves $\sim 10^4$.

3.3 Sensitivity to variations in the MF direction

The transition intensities and probabilities of the magnetosome existence in different states depend not only on the MF strength but also on its direction with respect to the

average orientation of the magnetosome. It is possible that this effect explains the ability of migrating animals to orient correctly during their prolonged travels in the absence of visual landmarks. Although numerous hypotheses exist, this phenomenon has not been reliably explained so far. The explanation of this phenomenon would solve partially the problem of biological efficiency of weak, lower than 1 G, MFs.

Consider again magnetosomes oriented predominantly oppositely to the direction of a permanent MF. We assume that $\varphi_0 = \pi - \eta$ (Fig. 1), where η is the angle by which the MF deviates from some reference direction specified by the bonds fixing the magnetosome in the average direction with respect to, for example, an animal skull. In the coordinate system connected with the geomagnetic field, η is the deviation angle of the animal orientation from the 'ideal' orientation related to the line of forces of the MF.

The equation of motion in the approximation of small angles η can be written in form (1) with the potential $U = \cos\varphi + \frac{a}{2}\varphi^2 - \eta\sin\varphi$. A change in the magnetic field proportional to η causes a change δU in the potential. The potential becomes asymmetrical. The probability ratio for the magnetosome existence in states $\varphi_\pm$ is

$$p_-/p_+ = \exp(2\delta U/D). \tag{2}$$

From this we can find the signal-to-noise ratio $R_{\rm sn} = 2U_1/D$, where $U_1 = \delta U/2 = \eta[6(1-a)]^{1/2}$ is the change in the potential level in one of the wells. The minimal detectable angle $\eta_{\min}$ of deviation from the reference course is determined by the equation $R_{\rm sn} = 1$.

It follows from this equation that

$$\eta_{\min} = \frac{D}{2[6(1-a)]^{1/2}}. \tag{3}$$

One can see that the maximum sensitivity to variations in the MF direction takes place for small values of a, i.e. for the high magnetic hardness. However, arbitrarily small values of a have no physical meaning.

Relation (2) and, hence, (3) are valid for the equilibrium probability distribution, i.e. the potential should change slower than the establishment of statistical equilibrium or relaxation. Here, we can distinguish relaxation within each of the wells with the time τ_1 and relaxation between the wells with the time τ_2. For small values of a, when the potential barrier is high, the relaxation time is determined by the longer of these two times, i.e. mainly by transitions between the wells. In this case, the characteristic time is the time of the first intersection of the barrier [53]

$$\tau_2 = \frac{2\pi}{[|U''(0)|U''(\pm\varphi)]^{1/2}}\exp\left(\frac{2U_0}{D}\right) = \frac{\pi\sqrt{2}}{1-a}\exp\left[\frac{3(1-a)^2}{D}\right].$$

The equilibrium distribution is realised under the condition $\tau_{\rm or} = \mu H t_{\rm or}/\gamma \gg \tau_2$, where $\tau_{\rm or}$ is the characteristic dimensionless time (in $\gamma/\mu H$ units) of the reorientation of an animal, the period of 'yaw' near the reference course. By assuming that $t_{\rm or} \geqslant 1$ s and taking into account the estimate $\gamma \sim 4\pi v r^3 \sim 20\times10^{-17}$ erg s [for the damping coefficient of rotations of a magnetosome of radius 10^{-5} cm in a liquid with the viscosity $v \sim 10^{-2}$ g cm^{-1} s^{-1} (water)], this condition is fulfilled for $a > 0.65$. Therefore, it follows from (3) that the error of deviation from the course is ~ 0.03 rad or 1.7°.

3.4 Temperature factor and magnetic noise effect

The stochastic resonance is characterised by the presence of a special interval in which $R_{\rm sn}$ drastically increases with temperature. However, variations in the temperature that can noticeably affect the value of the effect greatly exceed the admissible interval of physiological temperatures. Therefore, it is impossible to use temperature dependences to verify the stochastic resonance regime of magnetosomes. At the same time, it is very important to confirm the existence of such a dynamic regime of magnetosomes, which would also simultaneously confirm the involvement of nanoparticles in magnetoreception.

Consider the effect of the additional noise MF $\zeta(t)$ collinear to the alternating MF $\boldsymbol{h}$ with the correlator $\langle\zeta(t)\zeta(t+\Delta t)\rangle = \zeta^2\delta(\Delta t)/\omega$, where ζ is the root-mean-square amplitude of the magnetic noise and ω is the upper frequency limit of its spectrum (idealised white noise). The corresponding Langevin equation has the form

$$\gamma\dot{\varphi} - \mu H\sin\varphi + k\varphi - \mu h\sin(\Omega t)$$

$$= \xi'(t) + \mu\zeta(t) \equiv \xi''(t).$$

The calculation of the correlator for $\xi''(t)$ shows that in the presence of the magnetic noise the quantity $T' = T + \mu^2\zeta^2/(2\kappa\gamma\omega)$ is the effective temperature of the medium. Its value can be controlled by the level ζ of the magnetic noise and frequency ω. For the standard magnetosome of radius 10^{-5} cm, the effective temperature is doubled in the noise magnetic field of strength $\zeta \sim 1-2$ μT. This means that in the presence of a relatively weak noise, magnetosomes behave as if they were at a considerably higher temperature [54]. This can be conveniently used in experiments.

4. Interference of the angular molecular states

The interference or mutual amplification and quenching of waves is the general property of elastic, electromagnetic, and other waves for which the superposition principle is valid. According to the de Broglie hypothesis of the universal corpuscular-wave dualism, any material particles reveal the wave properties. The characteristic wavelength of a particle with the momentum p is $\lambda_{\rm B} = 2\pi\hbar/p$. Interference can be observed when the de Broglie wavelength is comparable with the observation system scale. This restriction does not allow one to observe the interference of macroscopic particles. At the same time, the interference of electrons, atomic beams, and even molecular beams, but not of their bound states is well known. Below, we consider the interference of the quantum states of angular modes of bound ions and molecules. Such interference has not been discussed earlier.

4.1 Interference of bound ions

Consider a particle inside an impenetrable sphere with a hole on which the particle potential decreases down to a certain finite value. The particle can overcome the potential barrier due to tunnelling. Because the tunnel transition probability depends on the probability density of finding the particle near a 'hole', the bound-state decay probability

is determined by the configuration of the wave-function density inside the cavity. The action of the MF on the shape of the 'probability cloud' changes the dissociation probability of an ion–protein complex. The results of many magnetobiological experiments and calculations within the framework of this model are in good agreement.

For most of the biologically important ions, the de Broglie wavelength even at 300 K is only three–six times smaller than the ion radius, being close to the dimensions of the effective potential of the binding cavity. Therefore, the ion dynamics at the atomic level substantially differs from classical dynamics, and ion states inside protein cavities should be described quantum-mechanically.

The reaction of ion binding by proteins, protein (..) + ion ⇆ protein (ion) consists in capturing the ion in the protein cavity formed by ligands. The biological activity of the protein in this state is changed. The ion enters the binding cavity through the 'gate' between oxygen ligands and after approximately 0.1 s it leaves the cavity. The model [46] is based on the assumption that the probability of ion escape depends on its state in the cavity (calmodulin hypothesis). Because of interference of the quantum states of the ion, the MF causes the redistribution of the ion cloud, thereby changing the equilibrium constant of the reaction.

The structure of some calcium-binding proteins is well known. The size of the region of motion of the calcium ion is small: the ion potential consists approximately by 80 % of the central potential $U(r)$ of radius 0.7 Å.

Consider the motion of an ion in an ideal cavity. Let q and M be the charge and mass of the ion with the intrinsic angular momentum I_n (in units of $\hbar$) and nuclear momentum μ_n. The Hamiltonian of a particle in a MF in the potential $U(r)$ is known:

$$\mathcal{H} = \frac{\mathcal{P}^2}{2M} + U - \hbar b \mathcal{L}\boldsymbol{H},$$

where $\mathcal{L} = -\mathrm{i}\boldsymbol{r} \times \nabla$ is the angular momentum operator and $b = q/(2Mc)$ is the ion parameter; hereafter, we assume that a spin is zero.

We can calculate the probability density of finding the ion near the 'gate' (i.e. for some value $\varphi = \varphi_0$) in the MF with $H_x = H_y = 0$ and $H_z = H_{dc} + H_{ac}\cos(\Omega t)$, where Ω is the MF frequency:

$$p(\varphi_0, t) = \sum_{mm'} a_{mm'} \exp\left\{\mathrm{i}\Delta m\left[\varphi_0 + \omega_L t + \frac{\omega_1}{\Omega}\sin(\Omega t)\right]\right\},$$

where $\omega_L = bH_{dc}$ is the Larmor frequency and $\omega_1 = bH_{ac}$.

We can show that on the average in time $\bar{p} = \text{const}$. This trivial result cannot be related to the properties observed in experiments. The way out is to take into account a nonlinear relation between the probability density $p(t, \varphi_0)$ and the probability P of the ion escape from the binding cavity in the dissociation reaction of the ion–protein complex. We will take into account only the linear and quadratic terms in the expansion $P(p) = P(\bar{p}) + P'_p\tilde{p} + \frac{1}{2}P''_{pp}\tilde{p}^2 + \ldots$, where $\tilde{p} = p - \bar{p}$. After the time averaging, we obtain $\overline{P} = c_1 + c_2\overline{\tilde{p}^2}$, where $c_{1,2}$ are constants. Of interest is the quantity $\tilde{p}^2$ (denoted below by $\mathscr{P}$) determining the dependence of $\overline{P}$ on the MF parameters. We will estimate it by taking into account that comparatively rapid oscillations of the density $\tilde{p}$ do not cause the nonlinear response of the protein and its conformation has no time to change. Therefore, it is reasonable to average first $\tilde{p}$ over some time interval $\bar{t}$ of the order of the response time and then to calculate the average square of the obtained value. As a result, we have in the dimensionless variables $h' = H_{ac}/H_{dc}$ and $\Omega' = \Omega/\Omega_c = f/f_c = f'$ that

$$\mathscr{P} = \sum_{mm'n} |a_{mm'}|^2 \frac{\sin^2 A}{A^2} J_n^2\left(\frac{\Delta m}{2}\frac{h'}{f'}\right),$$
$$A = \left(\frac{1}{2}\Delta m + nf'\right)\Xi. \tag{4}$$

Here, $\Omega_c = qH_{dc}/(Mc)$ is the cyclotron frequency; $f = \Omega/2\pi$; $f_c = \Omega_c/2\pi$; f' is the dimensionless frequency; $\Xi = \tau'\Omega_c$ is the dimensionless parameter; τ' is the rate constant of dissociation of the ion–protein complex; and J_n is the Bessel function of the order n. Figure 4 demonstrates the interference maxima at certain MF frequencies and amplitudes. These maxima are not resonances, i.e. they are not related to the resonance transfer of the oscillator energy from one mode to another.

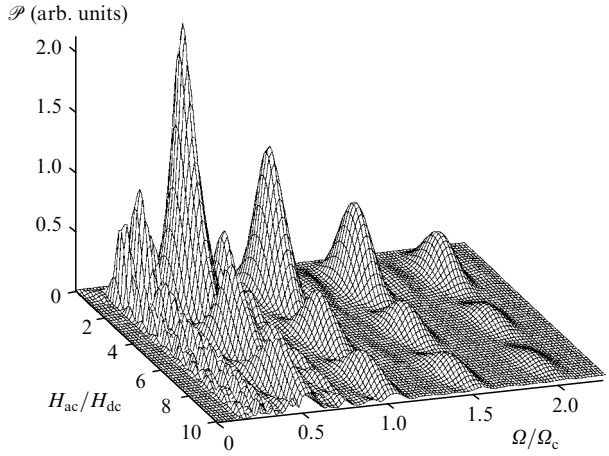

Figure 4. General view of the surface $\mathscr{P}(h', f')$ calculated from (4). The main interference maximum is located at $f' = 1/2$ and $h' = 1.8$.

If physicochemical perturbations caused by the MF are weak in some sense, the extremum in the dependence of the primary response to the MF will cause the similar extremum in the dependence of the biological response to the MF. Then, experimental data can be compared with the theoretical predictions concerning the 'magnetic conditions' for the appearance of the extrema.

According to the theory of interference of the angular ion states, the amplitude MBE spectra are independent of the type of ions involved in magnetoreception. This makes it possible to compare the data obtained for different biological systems with the same theoretical dependence. Within the accuracy of 10 %–15 %, this dependence is determined by the function $J_1^2(h')$. Figure 5 shows the calculated amplitude spectrum and experimental MBE data obtained by different authors at different laboratories for different biological systems under different 'magnetic conditions'. One can see that the theory and experiments are in good agreement.

In [6], the properties of interference in EMFs of different configurations were considered and it was shown that the

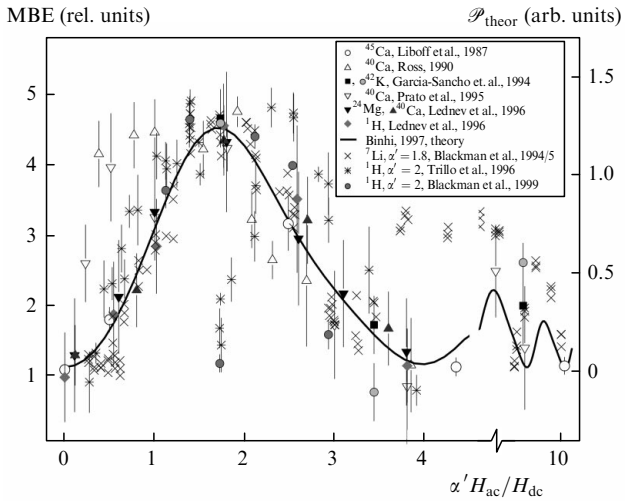

Figure 5. Experimental MBE in a uniaxial MF and the theoretical amplitude spectrum (solid curve) calculated for fixed ion–protein complexes with $\alpha' = 1$ and for rotating complexes with $\alpha' \neq 1$.

available experimental data were consistent with the calculations of the dissociation probability of ion–protein complexes in pulsed MFs, inclined permanent–alternating MFs, in a permanent MF and magnetic vacuum, in a noise MF, weak electric fields, in rotating ion–protein complexes, and microwave EMFs. The theory of the interference of angular ion states predicts spectral dependences which can be verified experimentally. At the same time, this theory is at present semi-phenomenological. It uses the assumption that the lifetime of angular modes is long and neglects physical processes providing the conservation of the angular-momentum projection on the MF direction. The validity of the theory of ion interference is justified by good agreement between calculations and experimental data. One of the possible justifications of its validity is related to the use of conservation laws in the dynamics of rotating bodies.

4.2 Molecular gyroscope

A device consisting of a rotating unit with fixed supports is one of the types of gyroscopes applied for measuring angular displacements and angular velocities. In our case, we are dealing in fact with a molecular gyroscope in which a relatively large molecular group is located in a protein cavity and the two edges of the group form covalent bonds (supports) with the cavity walls. It is important that the thermal vibrations of the supports produce only zero torques with respect to the intrinsic rotation axis of the group. Therefore, the gyroscopic degree of freedom is not thermalised by the thermal vibrations of the supports and the radiative decay is negligible.

The contribution to relaxation from Van der Waals electromagnetic forces produced by the wall vibrations was estimated by the molecular dynamics method. The thermalisation time increases exponentially with increasing the cavity radius b_c. The extrapolation to the region of large b_c shows that for $b_c = 14$ Å the thermalisation time and, hence, the relaxation time of the gyroscope or the coherence time of the rotational degree of freedom is ~ 0.01 s, which is sufficient for the manifestation of interference effects [55]. The rotating molecular group is represented here in the form of a rigid system of point charged masses – atoms in a molecule with partially polarised chemical bonds. For example, amino acid molecules could fit into quite spacious protein cavities by forming two chemical bonds at the remote ends of the molecule. The molecular Hamiltonian has the form

$$\mathcal{H} = \frac{\mathcal{L}^2}{2I} - \omega(t)\mathcal{L},$$

where

$$\omega = \frac{QH}{2Ic}; \quad I = \sum_i M_i r_i^2 \sin^2\theta_i; \quad Q = \sum_i q_i r_i^2 \sin^2\theta_i;$$

I and Q are the inertia moment and the 'charge inertia moment' of the system relative to the rotation axis, respectively; M_i and q_i are the mass and charge of the ith particle, respectively; and r_i and θ_i are its coordinates in the spherical coordinate system, respectively. The eigenfunctions of the time-independent part of the Hamiltonian are

$$|m\rangle = \frac{1}{\sqrt{2\pi}}\exp(\mathrm{i}m\varphi), \quad m = 0, \pm 1, ...,$$

and their energies are

$$\varepsilon_m = \frac{\hbar^2}{2I}m^2.$$

Consider a statistical ensemble of gyroscopes. Let us find first the density matrix $\sigma^{(\alpha)}_{mm'}$ of the gyroscope with the number α, then the probability of the gyroscope response, which nonlinearly depends on $\sigma^{(\alpha)}_{mm'}$, and finally, average the result over the gyroscope ensemble. We assume that the ensemble consists of gyroscopes which appear at a constant average rate at random instants in the superposition of states close to the ground state. In the representation of the eigenfunctions $\mathcal{H}_0$, the equation for the density matrix has the form

$$\dot{\sigma}_{mm'} = -(\Gamma + \mathrm{i}\omega_{mm'})\sigma_{mm'} - \frac{\mathrm{i}}{\hbar}\sum_l(\mathcal{V}_{ml}\sigma_{lm'} - \sigma_{ml}\mathcal{V}_{lm'}),$$

$$\omega_{mm'} = \frac{\hbar}{2I}(m^2 - m'^2); \; \mathcal{V}_{ml} = -\hbar\omega(t)m\delta_{ml}.$$

Here, the relaxation of the elements of the density matrix is taken into account only via the decay coefficients Γ. The solution of this equation is

$$\sigma_{mm'} = \sigma_{mm'}(0)\sum_n J_n(z_{mm'})\exp(-\beta' t),$$

where

$$\beta' \equiv \Gamma + \mathrm{i}\omega_{mm'} - \mathrm{i}(m - m')\omega_g - \mathrm{i}n\Omega;$$

$$z \equiv (m - m')\frac{h'}{\Omega'}; \; \Omega' \equiv \frac{\Omega}{\omega_g}; \; \omega_g = \frac{QH_{dc}}{2Ic}.$$

The probability density of the certain angular position φ of the gyroscope, which is favourable for the reaction with an active site on the cavity wall is

$$p(t) = \Psi^*(t,\varphi)\Psi(t,\varphi)$$

$$= \frac{1}{2\pi}\sum_{mm'n}\sigma_{mm'}(0)\exp[-\mathrm{i}(m-m')\varphi]\exp(-\beta' t)J_n(z_{mm'}).$$

Here, $\Psi(t,\varphi) = \sum_m c_m|m\rangle$ is the angular part of the wave function of the gyroscope. The moving-average method eliminates relatively fast density oscillations which do not affect a slow reaction with the active site with the characteristic time τ, i.e.,

$$p_\tau(t) = \frac{1}{2\pi}\sum_{mm'n}\sigma_{mm'}(0)\frac{\sinh(\beta'\tau)}{\beta'\tau}$$

$$\times\exp[-\mathrm{i}(m-m')\varphi]\exp(-\beta' t)J_n(z_{mm'}). \qquad (5)$$

Then, as in the ion interference model, we assume that the probability of the reaction of the side group of the rotating molecule with the active site of protein is a nonlinear function of the probability density (5). In the absence of any information on this function, we take into account the first nonvanishing term (quadratic one). To find the reaction probability, we take the square of (5) and average over the gyroscope ensemble:

$$p_\tau^2(t) \simeq \mathrm{e}^{-2\Gamma t}S',$$

where

$$S' = \sum_{mm'n}|\sigma_{mm'}(0)|^2\left|\frac{\sinh(\beta'\tau)}{\beta'\tau}\right|^2 J_n^2(z_{mm'}).$$

The factor S' in this expression contains the dependence on the magnetic field.

Let us assume that the gyroscope appears at the instant t'. Then, the probability (per unit time) of reaction at the instant t is

$$u(t,t') = S'\exp[-2\Gamma(t-t')], \quad t \geqslant t';$$

$$u(t,t') = 0, \quad t < t'.$$

By assuming that instant t' are distributed over the gyroscope ensemble in the interval $(-\theta,\theta)$ with the homogeneous density w, we find the averaged probability $\mathscr{P}$ by integrating over the parameter t':

$$\mathscr{P} = \lim_{\theta\to\infty} w\int_{-\theta}^{\theta} u(t,t')\mathrm{d}t' = \frac{wS'}{2\Gamma}.$$

The kinetic equation for the number of gyroscopes in the unit volume of a biological tissue $\dot{N} = w - \mathscr{P}N$ gives $N = w/\mathscr{P} = 2\Gamma/S'$ in the stationary regime. Let S'_0 and N_0 be the corresponding values in the absence of an alternating MF, i.e. for $h' = 0$. The relative change in the concentration ρ of the reaction products caused by the alternating MF is the relative number of gyroscopes involved in the reaction, i.e.,

$$\rho \equiv (N_0 - N)/N_0 = 1 - S'_0/S'. \qquad (6)$$

Analysis shows that at the frequencies $\Omega' = 2m$,

$$\rho = 1 - \left[1 + \frac{\sigma^2_{-m,m}(0)}{\sum_m \sigma^2_{mm}(0)}J_1^2(h')\right]^{-1} \qquad (7)$$

with an accuracy of 15 % – 20 %. The maximum value of the relative magnetic effect is 8.5 %, which follows from the assumption that the reaction probability depends quadratically on the probability density p of finding the gyroscope in a given angular position. Note that the probability of a chemical reaction is usually determined by the overlap integral of the electron wave functions of both reagents. If we assume that an active site of the gyroscope cavity is really 'active' and shifts to the molecular rotator proportionally to p, then the reaction probability is proportional to $\exp(-a'/p^2)$, where the coefficient $a' > 0$ is a parameter of the model. In this case, the relative magnetic effect (which is already maximally equal to 100 %) also depends on the model parameter a'. Its value, however, cannot be principally found from a comparison with experimental data. Only the dependences on the MF parameters can be compared. Therefore, a' is a 'redundant' parameter, which is reasonable not to use in the theory, as was done in the above model.

The main properties of the interference of gyroscopes and ions are the same. These are the presence of many extrema in the amplitude and frequency spectra, the dependence of the peak positions in the frequency spectra on the permanent MF strength and the independence of the positions of the maxima of the amplitude spectrum on the alternating MF frequency. The spectra can be always calculated for magnetic and electric fields of any configuration taking also into account intrinsic rotations of protein molecules, organelles, cells, and rotations of whole biological systems. The most important property of the interference of molecular gyroscopes is that it is relatively insensitive to molecular thermal perturbations. At present a molecular interfering gyroscope is probably the only molecular mechanism of magnetobiological effects which is physically consistent and well agrees with experimental data.

5. Conclusions

We have proposed and substantiated the mechanism of the stochastic resonance of magnetic nanoparticles found in the brain of animals and human beings. It has been shown that the properties of the nonlinear stochastic dynamics of magnetosomes, taking into account their viscosity-elastic fixing in a cytoskeleton, make it possible to explain the nonresonance effects of weak magnetic fields in the range from units to tens hertz in biological systems, the sensitivity of biological systems to geomagnetic variations and 'magnetic vacuum' conditions, as well as the ability of migrating animals to orientate in the geomagnetic field.

We have proposed and substantiated the interference mechanism of a molecular gyroscope. It has been shown that a low-frequency MF of strength comparable to the geomagnetic field and having the specially selected frequency and amplitude affects the interference of the states of a realistic molecular gyroscope, thereby considerably increasing the relative concentration of the reaction product at the physiological temperature.

These mechanisms are the examples of the construction of imaginary mechanisms of magnetoreception consistent with physical laws. Thus, we have proven that the 'κT problem': in its traditional formulation is inconsistent as the

argument against the possibility of magnetobiological effects.

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