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THEORETICAL CONCEPTS IN MAGNETOBIOLOGY

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ABSTRACT

It is well known that weak, about 1 G and less, magnetic fields (MFs) cause a biological response. Processes of different hierarchic levels of a living organism, from molecular (bio)physical to complex adaptive biological processes, contribute essentially to the effect of MFs on biology. In biophysics, separate magnetosensitive processes at the fundamental level of interaction of fields and substance are studied. It is exactly at this level that complex spectral or ‘‘window’’ modes of the relation between biophysical processes and biologically significant MF parameters originate. A review is given of the present situation. The paper concentrates on models that deal with extremely low frequency (ELF) MFs. Theoretical amplitude–frequency limits are considered that constrain possible physical mechanisms underlying biological effects.

INTRODUCTION

Different kinds of hypothetical explanations of magnetobiological effects[1] are known. This leads to a variety of conventional classifications of models in magnetobiology suggested by Polk (1), Adey (2), Berg and Zhang (3), and Blank (4). The presence of the classifications, their ambiguity, and their rapid obsoles-

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[1] Magnetobiological effect (MBE) is a collective term that is convenient to be equally applied to any biological effect of MF, and which displays dependence on the MF parameters regardless of the specific biological system responding to the stimulus.

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cence reflect the difficulties in explaining the MBEs, their paradoxical character, and the lack of knowledge of their physical nature.

Today, it is reasonable to pick out the following kinds of physical processes or ideas underlying hypothetically primary mechanisms of a biological magnetoreception:

- **macroscopic** Biomagnetite in MF and ferromagnetic contamination; Joule heating and eddy electric currents, induced by alternating MF; magnetohydrodynamics; macroscopic charged clusters and vortices in cytoplasm, and others
- **phenomenological** Bifurcation behavior of solutions of non-linear chemical kinetics equations; stochastic resonance as an amplifier mechanism in magnetobiology; phase transitions in biophysical systems displaying liquid crystal ordering; ''radio-technical'' models, in which biological structures and tissues are portrayed as equivalent electric circuits
- **microscopical** Classical and quantum oscillator models; cyclotron and parametric resonance in magnetobiology; interference of quantum states of bound ions, magnetosensitive free-radical reactions, coherent quantum excitations, biological effects of torsion fields accompanying MFs, biologically active metastable states of liquid water that are susceptible to MF variations

Table 1. Summary of Models of MBE Based on the Particle-Field Interaction

Variable-Dynamics	Classical	Quantum
	Lorentz force	*Interference of quantum states*
Coordinates	Particle deviation (Antonchenko *et al*., 1991) Polarization of oscillations (Edmonds, 1993; Lednev 1996)	(Binhi, 1997; Binhi, 1997a; Binhi, 1998; Binhi *et al*., 1998; Binhi, 1998a; Binhi, 1999)
	Energy pumping	*Quantum transitions*
Linear or angular momentum and energy	Cyclotron resonance (Liboff, 1985; Zhadin *et al*., 1990) Parametric resonance (Chiabrera *et al*., 1985; Zhadin, 1996)	Transitions in the Zeeman and Stark sublevels (Chiabrera *et al*., 1991) Transitions in atomic parametric resonance (Lednev, 1991; Blanchard *et al*., 1994)
		Spin dynamics
Spin	—	Nuclear magnetic resonance (Binhi, 1996) Radical pair reactions (Vanag *et al*., 1988) Nuclear spin dynamics in ion interference (Binhi, 1997)

Macroscopic MBE models form a more or less substantive group. Phenomenological models, on the other hand, require microscopic substantiation. Classical and quantum dynamics represents the basis for theoretical review of the microscopic effects. Practically all suggested microscopic MBE mechanisms are implemented as models. Classification inside this group of models in terms of type of dynamics used—classical or quantum, and type of variable, coupled with the MF, is therefore expedient. Such classification as shown in Table 1 is quite objective and consequently convenient for the comparison of models.

The depth of elaboration of the above-listed ideas in literature varies significantly. The predictive mathematical models support just a few ideas. All viable theoretical concepts variously relate to general physical limits constraining their applicability.

THEORETICAL MECHANISMS AND MODELS

Biogenic Magnetite and Magnetic Contamination

So-called biogenic magnetite was historically one of the first ideas in the area of magnetobiology. There are natural microscopic crystals, usually of magnetite, within the bodies of some animals and bacteria. They are capable of being magnetized. An external MF influences such crystals so that they tend to change their orientation. Consequently, the crystals exert pressure on the adjacent tissue and may cause a biological response. In a number of cases, Kirshvink *et al.* (5) explain in this manner the biological reception of a weak static MF. Microscopic crystals of magnetite are found in the brains of some birds, which are known to navigate well in the geomagnetic field. Traces of magnetite are also found in some insects.

Kobayashi *et al.* (6) proposed an explanation of the ELF MF effect on cells in vitro based on ferromagnetic contamination. Small polluting magnetic particles are present not only in the air dust; they are also deposited on the surfaces of laboratory devices, and penetrate into plastics and glass, into chemicals and purified water. Their mean size is about 10^{-5} cm. The particles consist of ferro- and ferrimagnetics; that is, they possess spontaneous magnetization. The authors have shown that routine laboratory procedures such as pouring and/or rinsing give rise to enrichment of the cell cultures by pollutants. The number of particles in cultures could be 10 times that of cells. The energy of such a particle is approximately three orders of magnitude greater than kT. In the author's opinion, a magnetic particle absorbed by a cell membrane can transfer its energy to the adjacent biophysical structures, for example, mechanically activated ion channels.

These mechanisms of MBE stand apart and do not solve the basic problem of magnetobiology. Indeed, many unicellular organisms, wherein magnetite is absent, are capable of reacting to MF. The reaction in many cases is complex and non-linear, depending on the MF parameters. The basic problem of magnetobiology is exactly in the explanation of this phenomenon, which is a paradoxical one from the viewpoint of orthodox physics.

Joule Heating and Eddy Currents

Low-frequency MFs induce eddy electric currents in biological tissues. They can also cause biological effects. In general, the magnitude of the current follows the electric field strength, which is directly proportional to the product of the AC MF amplitude and frequency. If the hypothesis is true, there must be a correlation between MBE and that product. Indeed, there is experimental evidence that such a correlation appears with the growth of the MF amplitude (7,8). However, no correlation has been observed for relatively weak, geomagnetic level MFs (9–14). So, in (11) the MBE at a certain frequency window was invariant even with a 40-fold change of the induced currents. This points to the existence of primary mechanisms irrespective of eddy currents.

Magnetohydrodynamics

These effects seen with the flow of blood or other bioplasma in MF were reviewed in (15). They are hardly useful to explain the MBE. To show this, let a frame of reference move in MF H together with fluid, with a velocity v. In such a frame there is an electric field equal to, in order of magnitude, $E \sim vH/c$. Generally speaking, the electric field could orient molecules with electric dipole moments, for example, water molecules with the moment $d = 1.855$ D. However, the energy dE, gained by a molecule in the electric field at geomagnetic values H and velocity ~ 1 cm/s, is fourteen orders below the thermal value of kT. Other writings take into account concentration of ions of opposite charge on opposite sides of a vessel. The work to displace a charge q on macroscopic distance r in a field E is equal to qrE, while the diffusion, which handicaps the displacement, has the same scale of energy as kT. It follows that there is thus the lack of five to six orders required to observe modification of ion concentration on walls, at the dimension $r \sim 1$–10 cm. The same pessimistic assessment is valid for clusters of ions that have been supposed in the literature to explain MBE. On one side the q/M ratio (M stands for the mass of an ion) is the same for a cluster of equivalent ions, while its energy is in direct proportion to the size of the cluster. In principle, it could be a rationale to overcome the kT problem. However, on the other side, no suitable physical reason has been proposed for forces that could assemble and retain the clusters as a physical entity.

Chemical Kinetics

The action of weak physical and chemical factors on biological systems displays an informational character (that is, no need to transfer much energy) that is frequently discussed in the literature. In this regard, a biosystem is assumed to be in a state of unstable equilibrium. Therefore, only a weak stimulus is required to put the system in a new state, at the expense of its intrinsic energy resources. In other words, the so-called biological amplification of a weak MF signal takes place. Chemical kinetic equations are used for the phenomenological description of this process. Under certain conditions, their solutions demonstrate a bifurcation behavior, the transition under weak disturbance into a qualitatively different dynamic mode. This was used by Kaiser to explain the MBE (16). Galvanovskis and Sandblom showed that the models can demonstrate complicated behavior with varying amplitude and frequency of the external stimulus (17). However, chemical kinetic models do not consider primary MF signal transduction to the biochemical level.

Stochastic Resonance

The phenomenon of stochastic resonance consists of the strengthening of a small signal against the background of noise, at the expense of energy redistribution within the frequency spectrum of the signal–noise mix. It is crucial that the noise here is a useful feature of the system, not an embarrassment. In the case of a stochastic resonance, relatively weak physical or biological signals can cause essential dynamic changes, against the background of many disturbing factors. In (18), the response of crayfish mechanoreceptor cells to an acoustic stimulus, in the form of the mixture of a subthreshold signal and a Gaussian noise, satisfied the attributes of a stochastic resonance. The phenomenon was used for solving the kT problem in magnetobiology in (19,20). However, only about 100-fold strengthenings were really achieved, with the loss of the quality of the signal; that is, its time coherence. Such values are obviously not enough to explain the biological efficacy of weak ELF MFs.

Phase Transitions

One must define molecular objects interacting with MF in order to use models with magnetosensitive phase transitions for the explanation of MBE. In diamagnetic biological media, such objects could only be molecules that are diamagnetic as well. It is known that phase transitions occur at the temperature T that is approximately defined by the interaction energy ε of neighboring molecules, that is $kT \sim \varepsilon$. However, what could be added to this energy due to MF interaction with diamagnetic moments of molecules is many orders of magnitude lower. Even if we consider a pile of *n* molecules, whose momentum is *n*-fold higher, only strong MFs on the order of 1 Tesla and more are able to change appreciably the ratio between ordered and disordered phases.

Radical Pair Reactions

It is known that the rate of some free radical reactions depends on the static MF (21). The probability of product creation from a pair of radicals, which carry spin angular momentum, depends on their net spin momentum, that is, on the mutual orientation of their spins. A static MF influences the probability of a suitable orientation, thus shifting the biochemical balance. At the same time, this mechanism does not possess frequency selectivity. The lifetime of the radical pair until reaction or, on the contrary, until dissociation, that is, when the bound couple of radicals are susceptible to MF, is of the order of 10^{-7} sec. The pair perceives the ELF-MF as a static field; no resonance appears. Therefore, Grundler *et al.* (22) and Kaiser (16) explain MBE frequency and amplitude windows assuming that the magnetosensitive free radical reaction is a link of the complex non-linear system described by chemical kinetic equations with bifurcation. Difficulties for this group of models stem from the primary MF influence on the radical reaction rate. There is a set of physico-chemical reasons that restrict susceptibility of the rate to MFs by quantities of the order of 0.1% per Gauss. It is not enough for MBE to be explained in a reliable manner.

Cyclotron Resonance

In a number of cases, the effects of weak MFs are resonant in character, and the effective frequencies are close to cyclotron frequencies of ions Ca^{2+}, Na^{+}, and others. Based on this, Liboff (23) assumed that a cyclotron resonance underlies the observable phenomena. Many authors developed the idea of such resonance in magnetobiology. Nonetheless, it has not received recognition due to the lack of rigorous physical substantiation. At the same time, these experiments showed the essential role of ions, especially Ca^{2+}, in magnetobiology.

McLeod *et al.* (24) studied ion behavior within a channel resembling the acetylcholine receptor, which has a constriction halfway along its length, constituting a bottleneck. This bottleneck could cause thermalizing collisions of ions with channel walls. Wall collisions are avoided by certain MF parameters, whose amplitude and frequency are predicted by the Lorentz force equation, which calculates coherent helical motion with known trajectory. This model predicted both frequency and amplitude MF windows required for the ion to ''fly'' through the channel. It was postulated that an ion starts from the channel mouth and moves along a spiral at the speed of about 10^{-7} m/s. The model is attractive but for its inconsistency with the Heisenberg uncertainty principle $\Delta x \Delta p \sim \hbar/2$, where Δx and Δp are uncertainties in the measured values of the x-coordinate of a particle and the corresponding linear momentum. According to this principle, a particle cannot possess arbitrary slow speed within a confined space. For a channel 50 Angstroms long a potassium ion must travel at a mean velocity that is no less than 0.1 m/s. This speed is many orders of magnitude higher than asserted by McLeod *et al.* to be the velocity of ion transit.

To overcome the weakness of the cyclotron resonance idea, macroscopic charged clusters or vortices formed by bunches of ions in biological plasma were postulated in (25). These targets for MF effects were chosen because of their relatively large self-contained energies, which may be comparable to kT. Then, even a weak MF can significantly change the energy of a vortex bearing, for example, a macroscopical electric charge. Yet strictly determined conditions of vortex movement are needed. In particular, the movement of the center of mass must be characterized by an angular momentum; otherwise MF cannot deliver energy to the moving object (26). It is doubtful that such a motion is real for a macroscopic object like a vortex in a bioplasma. Moreover, the comparison between the energy of a vortex and kT makes sense only with the existence of a conversion mechanism for that vortex energy to be transformed to the energy of a separate degree of freedom; that is, to the microscopic level. It is difficult to visualize such a mechanism. In addition, the physical nature of molecular forces, which could provide the existence and stability of the aforementioned clusters and vortices, is unclear.

Parametric Resonance

Some MBEs display windows of efficiency of the frequency and amplitude of the AC MF component. Frequency and amplitude spectra of MBEs are rather informative in terms of revealing the primary physical mechanisms of magnetoreception. For explanation of the MBE spectra, different conversion mechanisms of the MF signal were used at the level of microscopic dynamics. Classical and quantum models of ion binding by some proteins were studied by Chiabrera and Bianco (27), Chiabrera *et al.* (28), and Lednev (29). The biological activity of some proteins depends on whether or not an ion is bound with the protein. The value of MBE was assumed to follow the intensity of ionic quantum transitions. The MF was supposed to affect this intensity. However, colinear static and AC MFs affect only phases of wave functions, and do not really cause transitions in the Zeeman sublevels, or change intensity of such transitions induced by other factors. The population of each quantum state remains constant, regardless of the MF parameters. In spite of this, it was possible to demonstrate in (29) the similarity of the amplitude spectra of some MBE and those of the effect of the parametric resonance in atomic spectroscopy. The last resonance deals with quantum transitions; see, for example, Alexandrov *et al.* (30). This entailed a number of publications, which did not clarify the relationship, however. The authors call the above-indicated controversial mechanisms ‘‘parametric resonance of ions.’’

Ion Interference

In (31) the known phenomenon of the interference of quantum states is involved in the explanation of the physical nature of magnetoreception. MF, which is varied in its magnitude, not in direction, changes only the phases of ion wave functions. It is the interference that connects phase changes to physical observables in quantum mechanics. Earlier, the interference of quantum states was observed in physical measurements either for free particles, including relatively heavy particles up to atoms, or for bound particles. In the latter case, the interference was observed only indirectly, through the characteristics of reemitted electromagnetic fields. It reduced particles, suitable for the interference manifestations, to electrons in atoms. Binhi (31) suggested that the interference of bound heavy ions is also observable by means of indirect biological measurements, with involvement of natural active biophysical structures. This idea finds corroboration (32–34) in a good agreement with known experiments. The interference of bound ions may be regarded as a hitherto unknown physical effect that is detectable in principle only by means of biochemical or biological measurements. The interference of quantum states in atomic spectroscopy is related to coherent quantum transitions in atomic electron levels and is not related to the internal structure of electron wave functions. At the same time, it is the internal structure of ion wave functions that the ion interference is based on, even in the absence of any quantum transitions.

As of this writing, the ion interference mechanism predicts multi-peak biological effects in the following cases: magnitude/direction modulated MF, magnetic vacuum and magnetic noise, pulsed MF, weak AC electric fields, the shift and splitting of MBE spectral peaks under the rotation of biological samples, the interference of states of rotating rigid molecule, MF of the NMR frequency subject to spins of ionic isotopes, and bioeffects of modulated microwaves. The formulas provide the dependence of the ion-protein dissociation probability from the MF parameters, the frequency of the AC component, and the amplitudes and mutual orientation of the AC and DC components. Significant features of the MBE spectra calculated on the basis of the model depend on masses, charges, and magnetic momenta of the involved ions. In the cases under study, ions of calcium, magnesium, zinc, hydrogen, and sometimes potassium appear to be relevant. Appropriate biological effects have been observed in most experiments.

The consistency between theory and experiments indicates that what underlies the magnetosensitive ion binding is most likely the interference of ions. Unlike the *kT* problem, the question of why the approximation of long-lived angular modes of a central potential proves so close when applied to ions excited by thermal bath, is not a paradoxical question and is a subject of current study.

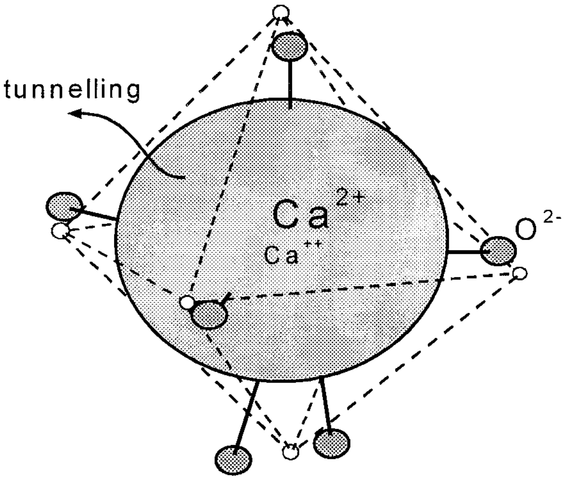

Figure 1. Coordination of ions in the calcium binding site in troponin C, after the data of Satyshur *et al.* (J. Biol. Chem. 263:1628). Ion Ca^{2+}, ligands O^{2-}, and virtual octahedron are shown holding proportions between ionic radii and ion–ligand distances.

The X-ray analysis of Ca binding proteins, calmodulin and troponin C, showed distorted octahedral Ca. co-ordination in binding sites (Fig. 1). There is only restricted room for the ion movements. It follows that the radius of effective confinement potential, <0.7 Angstrom, is about twice as large as the de Broglie wavelength of the Ca ion at room temperature. Therefore, ions in binding sites are quantum objects. Second, the radius of the ion is greater than that of the effective potential. This means that there is a correspondingly small value of deviation from the spherical symmetry of the potential. Third, an ion in such a small space appears to be excited by a thermal bath just in its lowest energy levels. Radial, azimuthal, and consequently magnetic numbers mostly do not exceed a few units; that makes the interference pattern coarse-grained and comparable with the ligand-to-ligand distances. This alters the probability of tunneling in specific magnetic conditions.

Coherent Excitations

Thermal fluctuations of the kT scale are ten orders greater than the quantum of the AC MF energy. In this case, the question is important—why do these random disturbances not destroy the MBE? Solutions suggested for the problem relate to the idea of coherence of the external stimulus, against the background of incoherent thermal noise. Then a high quality molecular oscillator may be swung up (time coherence) to a condition in which its energy will be sufficient for an initiating push. In addition, a system of oscillators may be swung up, in a time-space coherent manner, so that the quantum of a collective excitation will be released and utilized by subsequent biochemical process; see collection (35). Different microscopic objects have been suggested as oscillators interacting with MF: charged molecular groups, plasma membranes, and whole organelles. In the ELF-MF range, neither the idea of a biological oscillator nor the idea of collective coherent excitations has yet resulted in testable theoretical mechanisms. At best, time and amplitude thresholds (36) for the microwave exposure (37) are predicted, which are necessary for a biological response to occur.

Metastable Water States

Since water takes part in a variety of the metabolic biochemical reactions, changes in water state due to exposure to MFs may be transmitted further to the biological level. As of this writing, it is unclear what it is exactly in liquid water that could be the target for MF action. Based on observed low-frequency spectra of water electric conductivity, Fesenko and Gluvstein (38) discussed stable clusters of water molecules. The clusters were assumed to ''memorize'' an electromagnetic activation. Konyukhov *et al.* (39) considered spin-modified water, in which the natural composition between ortho- and para-modifications of water molecules was changed. Because the ortho-molecules possess a magnetic momentum, MFs do influence water in a resonant matter. Stable changes in structure properties of water were observed by Lobyshev *et al.* (40) using a UV luminescence spectrophotometer. Such changes have been attributed to different water structure defects that include specific centers of luminescence. Alterations in the biological activity of liquid water were found by Rai *et al.* (41) with static MF influence, and by Akimov *et al.* (42) after the influence of a domestic TV. In (43) the nuclear proton spins were considered as primary targets of MF. The metastability of water states was associated with microscopic orbital currents of protons in water-molecular hexagons, and the deviation from the right stochiometric composition of water. The existence of these states is verifiable in relatively easy experiments (44). The effects of ''memory'' of water, interacting with EMF, were observed in radio-frequency spectra by Sinitsyn *et al.* (45). The effect was proposed to originate from the oscillations of water-molecular hexagons.

Torsion Fields

There are theoretical and experimental prerequisites to assume the existence of so-called torsion fields [see references in (46,47)]. These long-range geometric fields can propagate independently and also accompany EMFs. The scientific area of geometrization of physical fields has existed since the last century. The general object of new theories, particularly Shipov's theory (46), is torsion fields, which stem from the known geometrical property of the space-time torsion. Mathematically, they are tensor fields that describe the curvature of space and so-called Ricci torsion, not the Cartan torsion of ordinary torsion theories. All the known fundamental fields and their equations appear here as some limit cases of the more general equations of torsion fields. Torsion fields originate particularly in spins of microparticles. Nonlinear extensions of the known fundamental equations, describing ''torsion effects'', may be derived from the general equations of torsion field. Note that torsion fields do not alter the energy of a quantum system involved in the interaction; they influence only phases of the system wave functions. In this case, a charged particle like the ion in a protein cavity interacts with an AC torsion field in a resonant manner (48). Energy is not an essential attribute of torsion fields. In particular, they do not obey the law of reciprocal squares. Therefore, the notion of magnitude is not specified for torsion fields: weak MFs thus affect biological systems via the torsion fields generated by those MFs.

CONCLUSIONS

Very weak MFs, at the level of 0.1 G and less, can affect biological systems; that is confirmed by an increasing number of studies. These data, schematically depicted in Figure 2, are of significant concern because they are hardly consistent

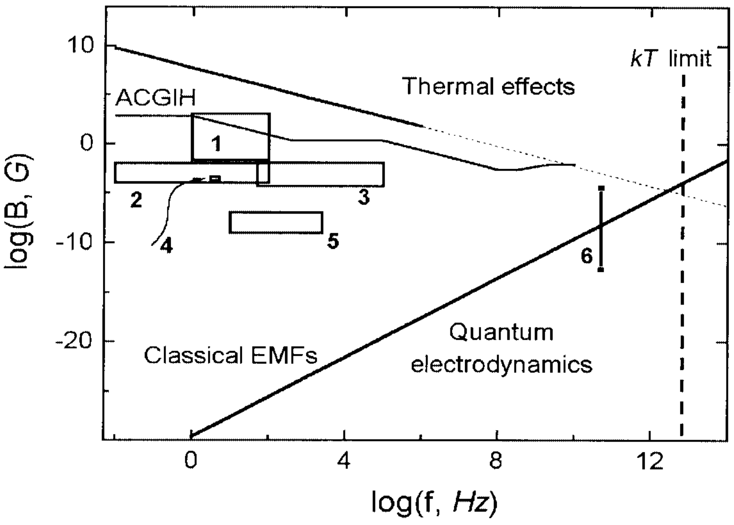

Figure 2. 1—ELF-EMFs used in most magnetobiological experiments; 2—EMFs produced by magnetic storms that are known to correlate in time with peaking of cardiovascular diseases; 3—background EMFs produced by a variety of home appliances, video display terminals such as TV and computer monitors; 4—MFs that affect some amino-acid solutions (49); 5—MFs calculated at 0.5 m from the TecnoAO protective device [patent No. 93/00546 France (50)], which protects against harmful VDT irradiation; 6—EMFs below a quantum electrodynamics limit, used in (51), that significantly affect cell culture. As is apparent, almost all the magnetobiology falls into the paradoxical area, to the left of the *kT* limit. A semiclassical approach might be sufficient to describe MBEs. However, the absence of the predictive primary physical mechanisms for MFs as small as 10^{-3}–10^{-10} *G* makes it attractive to apply torsion field physics for the MBE explanation.

with any of the proposed mechanisms. This poses the question of physical constraints defining the possible fundamental nature of the biological effects of hyperweak MFs. Figure 2 shows several theoretical limits of different mechanisms and descriptions of EMF bioeffects. They are shown as functions of two variables, EMF frequency *f* and amplitude of the magnetic flux density *B*. The *kT* and thermal limits are well known. The *kT* vertical line defines a paradoxical area wherein the biological effects are not possible from the orthodox viewpoint. The thermal limit has been derived repeatedly in many scientific studies and works on EMF standardization.

Interaction between EMF and a substance is classified within the different types of description, classical or quantum, both of EMF and field of matter. Most supposed primary mechanisms apply classical material particles to interaction with classical EMF, a wave field. Recent predictive mechanisms, which use the quantum description of ions in classical EMFs, are based on the so-called semiclassical approximation. QED, it sets conditions for a classical EMF description to be valid: populations of states of EMF oscillators must be sufficiently large compared to unit values. It follows that the relation that links the frequency and the classical amplitude of the magnetic EMF component is:

$$H > (\hbar c)^{1/2}(2\pi/c)^2 f^2.$$

This limit, the lower inclined line, is shown in Figure 2. As is apparent, all ''low frequency'' effects except the hyperweak MM radiation effects require only classical EMF description. However, this does not set the minimal intensity of EMFs detectable by biological systems. The natural constraint on the electromagnetic susceptibility of the biological reception, as well as that of any receiver of a physical nature, relates to general QM lows. There is the relation $et > \hbar$ between the minimal energy change *e* and the time *t* required for its registration. Consequently, for example, for an ELF-EMF photon at frequency *f* to be registered by any system (including a biological one), a time period of at least $t \sim 1/f$ is required. At the same time, this relation also does not set a lower limit for susceptibility to EMFs.

Apparently, there are no general theoretical constraints defining a lower limit for the intensity of EMFs affecting biological systems. All the physical constraints suggested to date are based on the proposed specific primary mechanisms of EMF signal transduction, not on first physical principles. Only the microscopic design of the biological receptor and the time of its coherent interaction with EMF define the level of hypersensitivity in each specific case. It is essential that the time of coherent EMF interaction with a biosystem be long enough to cause an effect due to the state of living matter which is far from the thermal equilibrium.

Torsion field physics apart, the most important and equally paradoxical problems concerning MFs at the geomagnetic level are as follows: (a) a mechanism or process of conversion of the MF signal to the biochemical response, whose energy scale *kT* is ten orders greater than the quantum of ELF-MF energy; (b) why thermal fluctuations of the same order as *kT* do not destroy the indicated weak signal conversion. At first sight, the paradox of the second problem is much more drastic, because an ''obvious'' solution of the first one is provided by signal

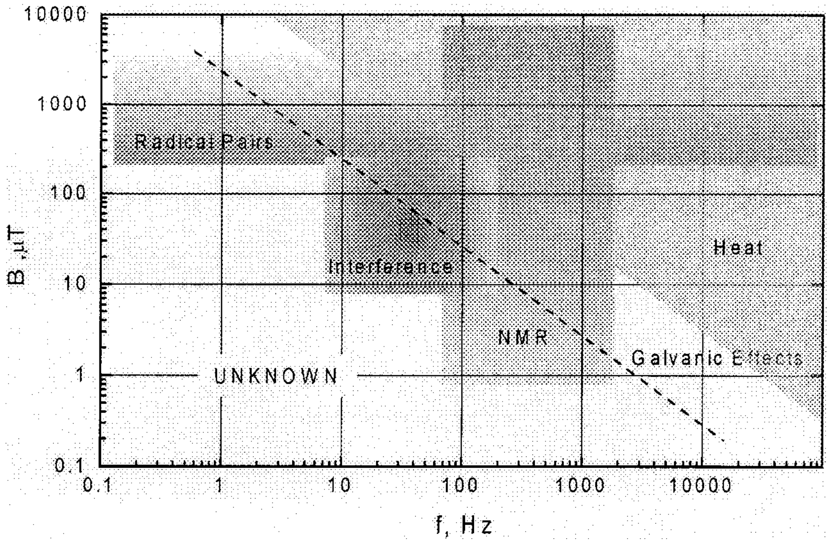

Figure 3. Physical mechanisms that hypothetically explain the MBE. Scopes of their efficacy are shown by grey shades.

energy storage or by signal amplification. Therefore, the main attention has been paid to solving the second problem, with the almost arbitrary choice of the conversion mechanism. However, it is the conversion mechanism that viable description of windowed multi-peak spectra depends on. This mechanism defines the predictive force of the model. Thus, as of today, there are no predictive models solving both problems simultaneously. At the same time, predictive models (31–34) have appeared; and they solve the first problem. This characterizes the current state of theoretical studies in the field of magnetobiology. The predictive force of such models means that the biological effects of weak MFs, as an important ecological factor, are becoming predictable as well.

It is convenient to arrange suggested physical mechanisms and their general limits, in accordance with their incidence, at the same plane of two variables of Figure 2. The mechanisms are seen to be restricted by different frequency-amplitude areas, Figure 3. Comparison of the figures shows that a major part of the available experimental data falls into the area of the so-called ion interference mechanism. To understand insensitivity to thermal fluctuations, we should take into account the ion–ligand interactions that not only confine the ion, but also lead to polaron-like excitations. Such a disturbance may propagate over angular variables inside the protein cavity like a soliton and be indestructible, as shown in (52), by thermal fluctuations in some limits.

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