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NUCLEAR SPINS IN THE PRIMARY MECHANISMS OF BIOLOGICAL ACTION OF MAGNETIC FIELDS*

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The initial stage of the primary mechanism of biological reception of magnetic fields is examined. Two possibilities exist for the transformation of the energy of the magnetic field into that of the orbital degrees of freedom of the particles which ultimately control the biochemical processes. Direct transformation admits of the classical analogy in the form of the Lorentzian force acting on the particle. Indirect transformation is associated with the spin of the particles. The power of the direct process approaches the quantum limit in the confined regions of biophysical systems adequately protected from the environment. It is shown that at these sites which are often key for biochemical reactions, the nuclear spins become a fundamental factor. The link between the phenomenon of the biological action of weak magnetic fields and the more general problem of the biological efficacy of weak physicochemical factors is discussed.

INTRODUCTION

It is known that the parameters of the vital activity of biological systems correlate with geomagnetic variations [1, 2] and even with change in the characteristics of the interplanetary magnetic field [3, 4]. The nature of this important phenomenon is at present unclear. One of the possible explanations is linked with the direct effect of a weak magnetic field on the state of the biological system. The primary mechanism of such an action is based on the interaction of an electromagnetic field (e.m.f.) with the substance, i.e. with atomic nuclei starting from a proton and with electrons. The most profound description of the interaction of an e.m.f. with particles of matter with the spin 1/2 is associated with the representation of the latter in the form of the Dirac spinor field. This describes electrons within the framework of quantum electrodynamics and, in addition, gives a phenomenologically correct description of protons on the atomic scale.

The Lagrangian of the interaction of an e.m.f. with the spinor field is established from the requirement of invariance of the theory in relation to the local phasic transformation of the spinor field and has the form

$$\mathfrak{L}(x) = eA_{\mu}(x)J^{\mu}(x),$$

where e is the electron charge, $A_{\mu} = (A_0, \mathbf{A})$ is the four-potential e.m.f., J^{μ} is the field current of the particles. In Hamiltonian semiclassical formalism such a Lagrangian leads in essence to replacement of the pulse operator $\mathbf{p}$ by the "elongated operator" $\mathbf{p} - (e/c)\mathbf{A}$.

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Since the velocity of the particles forming the biological system including electrons, $v \ll c$, the relativistic effects can only be minor corrections to "slow dynamics". Therefore, the components of the wave function of the particle in the e.m.f. after the substitution mentioned in the Dirac equation is described as the non-relativistic approximation. With an accuracy to terms $\sim c^{-2}$, it reduces to a Schrödinger equation with the Hamiltonian

$$\boldsymbol{H} = \boldsymbol{H}(\mathbf{r},\mathbf{p}) + \boldsymbol{H}(\mathbf{p},\mathbf{A}) + \boldsymbol{H}(\mathbf{s},\mathbf{A}) + \boldsymbol{H}(\mathbf{s},\mathbf{r},\mathbf{p})$$

where **r**, **p**, **s** are variables in the space of the coordinates, pulses and spins, respectively, $\boldsymbol{H}$ (**r**, **p**) describes the dynamics of the orbital (**r** and **p**) degrees of freedom in a certain fixed potential, $\boldsymbol{H}$ (**p**, **A**) gives the change in this dynamics under the influence of an e.m.f. $\boldsymbol{H}$ (**s**, **A**) defines the dynamics of the spin of the particle in the e.m.f. and, finally, $\boldsymbol{H}$ (**s**, **r**, **p**) describes the interaction of the spin and orbital degrees of freedom.

Already at this stage variants of the mechanisms of action of the e.m.f. on the orbital degrees of freedom exist. The last degrees determine the course of the biochemical processes and control in mediated fashion the behaviour of biological systems. In this work it is assumed that the biological reaction to the action of an alternating magnetic field is due in the final analysis to absorption of the energy of the magnetic field, however small it may be, and to its transformation to the energy of the orbital degrees of freedom. (An alternative view is that exposure to the magnetic field changes the trajectories of the particles or the "trajectories" of the spin degrees of freedom [7]. The interaction of the magnetic field in principle possible and discussed in the literature with collective excitations in biophysical systems [8] includes the interaction of the magnetic field with individual particles as its basis.) Such transformation is limited only by two possibilities. The first is linked with the terms $\boldsymbol{H}$ (**r**, **p**), $\boldsymbol{H}$ (**p**, **A**) and has the classical analogy in the motion of a point particle in the potential relief under the influence of the Lorentzian force

$$\mathbf{F} = e\mathbf{E} + \frac{e}{c}[\mathbf{vH}],$$

where **E**, **H** are the electrical and magnetic fields.

The second, purely quantum, possibility is linked with the terms $\boldsymbol{H}$ (**s**, **A**) and $\boldsymbol{H}$ (**s**, **r**, **p**). We have in mind that the energy of the magnetic field is at first converted to the energy of the spin degrees of freedom and then already to the energy of orbital motion through the spin–orbital interaction $\boldsymbol{H}$ (**s**, **r**, **p**). The dynamics of the spin degrees in itself is not observable but is manifest in the interaction with the orbital degrees of freedom. Therefore, the relatively minor interaction $\boldsymbol{H}$ (**s**, **r**, **p**) is crucial.

Most existing models and ideas on biomagnetic effects are constructed on the classical dynamics of the charged particle in the magnetic field [5, 6]. The resonance properties of various high quality oscillatory biologically significant structures are considered here. Usually, it is assumed that any variant of the link of the magnetic field and the dynamics of the oscillatory system is capable against the background of the high quality of the system (i.e. profound isolation from the thermal oscillations of the medium) or against the background of collective effects (biological coherence of any nature) of leading to pumping of the oscillations sufficient in their amplitude to shift a certain link of metabolism. Yet, as will be shown below, the values of the possible contributions to orbital dynamics over both routes are amenable to quite a correct estimation in the sense of the power of the process of transformation of the energy of the magnetic field. This factor is just as important for the final biological reaction as the quality of the oscillatory biophysical system and the effectiveness of biological coherence. In addition, individual experiments indicate the crucial nature of the spin resonance mechanisms of primary reception.

The question of the possible role of spin magnetic resonances in biomagnetic effects has a definite history. The first experimental work in this direction was apparently undertaken in 1982 in Salford University [9]. Dielectrophoresis on *E. coli* cells carried out at frequencies and in magnetic fields satisfying the conditions of nuclear magnetic resonance (NMR) demonstrated distinct resonance features. Frequency dependences of the dielectric losses on living *E. coli* cells also revealed deviations appearing in the magnetic field at NMR frequencies for the ^{1}H, ^{23}Na nuclei and others. The effect of the magnetoresonance conditions on the lifetime of the generation of *E. coli* and on a particular enzyme reaction was demonstrated. Unfortunately, these experiments were only partially developed in [9] and [10] and have not been reproduced by other authors.

In [11–14] the effect of alternating magnetic fields of complex configuration on diverse biological objects was explored. It was found that the details of the configuration of the magnetic field essential for the response of a biological system are: (a) the dependence of the frequency of the effective magnetic field on the size of the constant field, (b) the reciprocal orientation of homogeneous alternating and constant magnetic fields and (c) the state of polarization of the alternating e.m.f. [15]. We would note that the significance of the factors listed also applies to the phenomenon of spin magnetic resonance. The low frequency range (below 100 Hz) of effective magnetic fields and the short lifetime of the unpaired electron states in a living medium make improbable the participation in these phenomena of electron spins, although the problem of the possible role of radical pairs and triplet states in biomagnetic effects has not been finally resolved [16]. According to the estimations of [17], only a sufficiently strong alternating magnetic field of about 1 kgauss is capable of appreciably changing the rate of the radical reaction.

Several studies relating to the idea of NMR in biomagnetic effects were considered in [18, 19]. In [16] the authors noted the problem of the uncontrolled influence of medical NMR-tomography on the patients studied.

Important studies discussing in one way or another the possible role of magnetic resonances in biology are known [20, 21].

The tenets of the hypothesis on the spin mechanism of the primary reception of the magnetic field are indirectly further reinforced by the fact that the mechanisms associated with the action of the Lorentzian force on ions in solution are considered impossible [22].

Thus, the idea of considering nuclear spins or the phenomenon in which they are most conspicuous — NMR — in connection with the primary mechanism of reception of the magnetic field is not new. Development of this idea is difficult, although it is clearly realized that in the terrestrial magnetic field NMR radiospectrometers do not work in practice. The question arises: is it permissible, in general, to speak of resonance if it is not observable under these conditions, i.e. can we not isolate the characteristic absorption signal? Is a situation conceivable in which not the spectrometer but a living system is a detector of spin dynamics?

FEATURES OF THE MANIFESTATION OF NUCLEAR SPINS IN A WEAK MAGNETIC FIELD

The elementary NMR theory adds up to a description of the permissible spin states of a microparticle (we shall consider the proton — ^{1}H nucleus) in a constant magnetic field $\boldsymbol{H}$. The spin states are defined by the solutions of Schrödinger's equation

$$-M\mathbf{H}\psi = \varepsilon\psi, \quad \psi \equiv \begin{pmatrix} f \\ g \end{pmatrix}, \tag{1}$$

where ψ is a wave function of the proton with the components f and g which correspond to the spin states with projection along and against the arbitrary direction z, ε are the permissible values of the energy of the spin, and M is the magnetic moment operator.

The operator M is linked with the spin operator S by the relation $M = \frac{\mu}{s} S$. The value of the ratio of the magnetic moment of the proton $\mu = 1.41 \times 10^{-23}$ erg·gauss^{-1} to its spin $s = 1/2$ is called the gyromagnetic ratio γ. Let us assume that the magnetic field **H** has only one z- component H. Then equation (1) has two solutions

$$\varepsilon_1 = -\frac{\gamma}{2}H, \quad \psi_1 = \begin{pmatrix}1\\0\end{pmatrix}, \varepsilon_2 = -\frac{\gamma}{2}H, \quad \psi_2 = \begin{pmatrix}0\\1\end{pmatrix}. \tag{2}$$

Let the spin be initially in a certain state ψ_1 or ψ_2. If now to the constant field $\boldsymbol{H}$ is applied a small field $\mathbf{h} \perp \mathbf{H}$ rotating to one (strictly defined!) side about the axis $z \| \mathbf{H}$ with the frequency $\omega \approx \frac{\Delta\varepsilon}{\hbar}$, then the probability of the spin being in the state ψ_1 (or ψ_2) begins to oscillate. It is also said that quantum transitions appear between the states ψ induced by the alternating magnetic field. The amplitude of the oscillations of probability (or the intensity of the transitions) reaches a maximum in resonance when the frequency ω is strictly equal to $\omega = \frac{1}{\hbar}\gamma H$. The frequency of the oscillations of probability depends on the amplitude of the alternating field: $\Omega = \frac{1}{\hbar}\gamma h$.

The slight interaction of the spin ensemble with the thermostat governs the process of energy relaxation of the spin system on which is also based the work of NMR radiospectrometers. Observation of the absorption signal in the spectrometer is ensured by a certain balance of the processes of pumping of the quantum transitions and the processes of spin-lattice relaxation. The quantum transitions induced by an alternating magnetic field tend to equalize the populations of the Zeeman levels. Spin-lattice relaxation on which is based the spin–orbital interaction — relativistic effect of the order c^{-2} — tends to return the populations to a balanced Boltzmann distribution. The difference in the populations at $T \sim 300$°C $\Delta n \sim H$; the absorption signal is proportional to $(\Delta n)^2$ and rapidly drops with fall in the magnetic field from the values $H \sim 0.5 \times 10^5$ gauss usual for spectrometers. In the earth's magnetic field, which is lower by five orders, the levels are actually equipopulated and the realization of the conditions of resonance of the ^{1}H nuclei in liquid water, for example, does not lead to the appearance of an appreciable signal. (Means of observing the resonance signals from ^{1}H nuclei in the earth's field [23, 24] are known using large water masses.)

The question arises: is it permissible at all in this case to speak of any resonance? This is quite permissible if one finds another macroscopic parameter differing from absorption experiencing resonance behaviour on frequency scanning. What parameter might this be?

First let us define what gives rise to the absence of energy absorption for an equipopulation of levels. Firstly, we would note that the rate of energy absorption in the sample is an additive parameter summing the contributions of the individual microsystems of the ensemble. With the condition of equipopulation, the quantum transitions of the individual spins on exposure to a resonance field still take place despite the absence of absorption. The probabilities of finding spin at both levels oscillate, amounting in sum to unity. This means that each spin periodically increases and reduces its energy, gathering or donating it to the resonance field. However, all the spins forming the ensemble oscillate discordantly and have an equiprobable distribution over the levels.

The summation of the energy transmitted to the field by the spins is equivalent to the mathematical procedure of averaging over the ensemble of spins the magnitude linearly associated with the probability of its quantum states. The consequence is the absence of energy transmission.

How in these conditions might one determine whether resonance transitions occur in the ensemble? If one could manage to place next to each spin a local probe or element the states of which would depend non-linearly on the probabilities of the spin states (for example, the chemical process realized in accord with the rules of spin selection) and then average over the ensemble of probes, we would as a result obtain a value somehow associated with the amplitude of the oscillations of probability of spin states, i.e. with the resonance situation. It is important to note that this magnitude, in general, would no longer be equal to zero on exposure of the spin ensemble to the resonance field, even for equipopulation of levels. Such a method of detecting oscillations of the spin states resembles detection of a radiosignal with the aid of a diode, which it non-linearly transforms and an averaging capacitor.

The possibility of detecting resonance through local probes does not change as such if not all the spins but only a sufficient proportion of them is linked with their own probes. Such a situation does not change qualitatively if the individual local probe has comparatively large dimensions and is connected at once to several spins of the ensemble. One might even go further concluding that only a certain "active element" of the probe corresponds in its dimensions to a group of spins which interact with it. These dimensions are $\sim 10-20$ Å if the density of protons in water is heeded. The rest of the probe may have larger dimensions and act as a non-linear converter of the states of the active element into the macroscopic states of the probe itself.

What further properties must a local probe possess to be an effective detector of spin dynamics?

1. It is clear that the degrees of freedom of the active centre of the probe which interact with the spins must be spatial degrees of freedom (one still says orbital); otherwise perusal of local probes would be meaningless. It is also clear that the spin–orbital interaction is responsible for changes in the state of the probe as a consequence of changes in the spin ensemble.

2. The degrees of freedom of the probe interacting with the spins must not be perturbed by thermal oscillations of the medium greater than the spins themselves. That is regardless of the interaction with spins, the lifetime proper or the characteristic time scale of the dynamics of the orbital degrees of freedom must, at least, be not less than the longitudinal relaxation time of the spins and better exceed T_1 by a further order of magnitude. Then the probe could act as an integrator of the changes in the states of the spins associated with it.

3. The energy scale of states of the degrees of freedom of the active centre which interact with the spins corresponds to the scale of the Zeeman energy of the spins and the latter in the earth's field is very low $\sim 10^{-23}$ erg. The states of the orbital degrees of freedom of the active centres for this simple reason are just as inconspicuous in direct measurement of anything physically observable as is the NMR absorption signal in the ensemble of spins. Therefore, change in the states of the probes themselves as a result of their interaction with the spins in resonance conditions will be appreciable if the probes perform the function not only of a non-linear converter but also power amplifier of the processes taking place within it.

In other words, the probe must contain non-linear and integrating elements in relation to the disturbances introduced by the spin–orbital interaction. Then the effect of the latter will accumulate and, enhanced, will lead sooner or later to appreciable changes in the state of the probe.

Thus, the properties of the probe which might ensure its use as a detector of ^{1}H spins are: (a) small dimensions of the active centre of the order of about 10–20 Å; (b) the presence of orbital degrees of freedom which interact with the ^{1}H spins, on the one hand, and are non-linearly linked with the states of the probe, on the other; (c) prolonged lifetime of the excited orbital states $\tau \gg T_1$, i.e. their metastability; and (d) the presence in the probe of a non-equilibrium system ensuring enhancement of the processes in the non-linear converter.

Irreversible biochemical reactions create favourable conditions for the so-called biological enhancement of weak signals. On the other hand, they are quite microscopic. In turn, many biophysical molecular systems ensuring an adequate course of biochemical reactions have, as it were, regions protected from external perturbations. The presence of metastable degrees of freedom in them appears plausible. Apparently, there are no fundamental prohibitions restricting the interpretation of biophysical molecular systems as primary magnetic field receptors with the participation of spin degrees of freedom.

The ion channels of biological membranes have for long been the object of the search for the primary mechanisms of action of the magnetic field [7]. There is direct experimental evidence of a change in the activity of some ion channels under the influence of weak magnetic fields [25, 26]. Ion channels are convenient for quantitative estimations. They possess physical properties which permit idealization in the form of a simple mathematical model. In this case, it is possible to show that the nuclear spin of an ion leads to change in the energy of its movement in the magnetic field.

EFFECT OF THE SPIN OF A PROTON ON ITS PULSE DURING ONE-DIMENSIONAL MOVEMENT IN A MAGNETIC AND NON-UNIFORM ELECTRIC FIELD

The Hamiltonian of an electron with an external e.m.f. in the non-relativistic approximation with reference to terms of the order of about c^{-2} has the following form [27]

$$H = \frac{\left(\mathbf{p} - \frac{e}{c}\mathbf{A}\right)^2}{2m_e} - \frac{\mathbf{p}^4}{8m_e^3c^2} + eA_0 - \frac{e\hbar}{2m_ec}\sigma\mathbf{H} + \frac{e\hbar^2}{8m_e^2c^2}\Delta A_0 + \frac{e\hbar}{4m_e^2c^2}\sigma\left[\nabla A_0\left(\mathbf{p} - \frac{e}{c}\mathbf{A}\right)\right], \tag{3}$$

where $\mathbf{p} = -i\hbar\nabla$ is a pulse operator, σ are Pauli matrices, $\mathbf{A}$, A_0 are vector and scalar e.m.f. potentials, and $e = -|e|$ is the electron charge.

Formally, passage to the description of a proton using (3) is achieved by the substitution $e \to |e|$; $m_e \to m_p$. However, in those terms of the Hamiltonian which describe the interaction of the external field with the magnetic moment proper of the particle, it is necessary to replace the combination $\frac{e\hbar}{2m_ec}$, which represents the intrinsic magnetic moment of the electron by the real magnetic moment of the proton μ. It anomalously differs from $\frac{|e|\hbar}{2m_pc} \equiv \mu_N$ and is equal to 2.793 μ_N. The operators $\sim\sigma$ refer to the Hamiltonian terms mentioned. The classical interpretation of these operators consists in the interaction of the magnetic moment with the magnetic field for the operator $\sim\mathbf{H}$ and in the interaction of the moving magnetic moment with the electric field for the operator $\sim\mathbf{E} = -\nabla A_0$ — the operator of the spin–orbital interaction. This becomes obvious in

the system proper of coordinates of the moving particle in which the additional magnetic field appears.

We shall assume that the external field $\mathbf{A}$, A_0 is created by sources which are outside the region of movement of the proton, next the operator $\sim \Delta A_0 = 0$ may then be omitted. We also omit the operator $\sim \mathbf{p}^4$, since it introduces corrections of the order c^{-2} to those estimations which will be obtained. If calibration transformations linking $\mathbf{A}$ to A_0 are no longer used, one may also omit the last term in (3) $\sim c^{-3}\sigma\,[\nabla A_0 \mathbf{A}]$. This is the interaction of the spin with the e.m.f. and, therefore, offers a minor correction to the term $\sim \sigma \mathbf{H}$. Having regard to all this the Hamiltonian of the proton in the e.m.f. assumes the form

$$H = \frac{\left(\mathbf{p} - \frac{e}{c}\mathbf{A}\right)^2}{2m} + eA_0 - \mu\sigma\mathbf{H} + \frac{\mu^2}{e\hbar}\sigma[\nabla A_0 \mathbf{p}], \tag{4}$$

where $e = |e|$, and m are the charge and mass of the protein, respectively.

We are interested in change in the energy of the orbital movement of a proton in response to an alternating magnetic field. This part of the energy is obviously $\sim \mathbf{p}^2$. The operator of the derivative of the square of the pulse in accord with the general rules of differentiation of operators in time is equal to

$$\dot{\mathbf{p}}^2 = \frac{\partial \mathbf{p}^2}{\partial t} + \frac{i}{\hbar}[H, \mathbf{p}^2]$$

Since $\mathbf{p}^2$ does not explicitly depend on time, $\dot{\mathbf{p}}^2$ is proportional to the commutator of the Hamiltonian (4) with $\mathbf{p}^2$. It is convenient to choose the calibration of potentials $\mathbf{A}$, A_0 in the form of $\nabla \mathbf{A} = 0$. The commutator differs from zero for several terms of (4). Below we use tensor algebra of operators in three-dimensional Euclidean space so that the position of the superscripts and subscripts is dictated only by convenience of writing. It may be shown that

$$[H_{pA}, \mathbf{p}^2] = \left[\frac{\left(\mathbf{p} - \frac{e}{c}\mathbf{A}\right)^2}{2m}, \mathbf{p}^2\right] = -\frac{e}{mc}[\mathbf{Ap}, \mathbf{p}^2] + \frac{e^2}{2mc^2}[\mathbf{A}^2, \mathbf{p}^2] = \tag{5}$$
$$= \frac{e}{mc}\left\{A^i_{,kk}p_i + 2A^i_{,k}p_k p_i - \frac{e}{c}\left(A^k_{,i}A^i_k + A_k A^k_{,ii} + 2A_k A^k_{,i}p^i\right)\right\},$$

where we put $p_k \mathbf{A}^i \equiv A^i_{,k}$. This is meaningful in as much as $p_k = -i\hbar\frac{\partial}{\partial x^k}$.

$$[\mathbf{H}_E, \mathbf{p}^2] = [eA_0, \mathbf{p}^2] = eA^i_{0,i} + 2eA^i_0 p^i \tag{6}$$
$$[\mathbf{H}_{sA}, \mathbf{p}^2] = [-\mu\sigma\mathbf{H}, \mathbf{p}^2] = \mu\sigma_k\left(H^k_{,i}p^i + 2H^k_{,i}p^i\right).$$

For a uniform magnetic field all the H^k derivatives along the coordinates are equal to zero and hence so is the last commutator

$$[H_{spr}, \mathbf{p}^2] = \frac{\mu^2}{e\hbar}\sigma_k e^{ijk}\left(E^l_{i,l} + 2E_{i,l}p^l\right)p_j. \tag{7}$$

Change in the orbital energy is thus the consequence of:

(1) the direct effect of the magnetic field which is connected with the term (5) of the commutator $[H, \mathbf{p}^2]$; (2) the direct effect of the electric field — (6); and (3) the indirect effect of the magnetic field through the spin of the particle — (7), which is possible in a non-uniform electric field.

It is clear that the relative contributions of the different terms $\dot{\mathbf{p}}^2$ to change in the orbital energy depend on the specific model situation. It is desirable to choose a model which would be

relatively simple, not too far from the real situation and would emphasize the indirect effect of the magnetic field of interest to us through the spin-particles. Probably, such a model might consist in the idealization of the movement of an ion, for example, a proton, through the ion channel of the biological membrane. It is known that ion channels are represented by portions of protein molecules coiled into a helix so that these helical portions intersect the membrane and allow the ions to penetrate through it. It is important to note that the electric field within the ion channel has not only an axial component produced by the potential difference on the inner and outer surfaces of the membrane but also a transverse helical component. Apparently, it is governed by hydrophilic areas of different polarity on the surface of the protein molecule turned into the helix. We would also note that the length of the channel is usually 5–10 times greater than its diameter.

Let us consider the unidimensional movement of a proton along the z axis and let us carry out the formal transition by the rule $x = y = 0$[4] for the coordinates of the proton and $p_i = 0$, $i \neq 3$. (The use of the general Dirac method for investigating quantum systems with links [28] gives similar results.) Let us suppose that the constant uniform magnetic field is directed along the z axis and the alternating component turns* about this axis with the frequency ω which corresponds to NMR conditions for $\omega = \frac{1}{\hbar}\gamma H_z$.

The constant electric field **E** has a transverse component the direction of which depends linearly on z (spatial helix).

The condition div **A** determines the potential for the given magnetic field incompletely. It is obvious that $\mathbf{A}' = \mathbf{A} + \text{rot}\,\mathbf{B}$, where **B** is the function of the coordinates, and also corresponds to rot $\mathbf{A}' = \mathbf{H}$ and to the condition div $\mathbf{A}' = 0$ if rot (rot **B**) = 0. It is convenient so to choose **B** that $A_3 = 0$. Let us direct the unit vectors $\mathbf{e}_i$, $i = 1, 2, 3$, along the x, y, z axes, respectively. Next if

$$\mathbf{H} = (H_1, H_2, H_3) = (h\cos\omega t, h\sin\omega t, H), \tag{8}$$

then

$$A = (hz\sin\omega t - \tfrac{1}{2}Hy, \quad hz\cos\omega t + \tfrac{1}{2}Hx, 0). \tag{9}$$

Let

$$\mathbf{E} = (E\cos\xi z, E\sin\xi z, 0), \tag{10}$$

here $\lambda = \pi/\xi$ is the spatial period of the helix. The definition of **E** in the form (10) is an idealization, since it is apparently impossible to construct A_0, satisfying $\mathbf{E} = -\text{grad}\,A_0$ in the entire space. This circumstance nevertheless contradicts nothing. From (10) we find $A_{0,3} = 0$, then the commutator (6) = 0, i.e. the transverse electric field entails no change in the energy of the particle. The problem is to understand how significant are the effects of nuclear spin and, therefore, it is sensible to introduce idealization of an infinitely long channel. This also means $E_3 = 0$ and the absence of a potential function of the particle. Probably, calculation outside this idealization requires the use of numerical methods for solving the equations in partial derivatives.

There is a further difficulty. The potential A_0 as an operator is well defined in the space of one-dimensional wave functions, since its effect adds up to multiplication by E_3. In fact, change

* Allowance for the rotating component of the magnetic field is not a restriction: one may also consider a linearly polarized alternating magnetic field. In this case the spin dynamics is in a certain respect similar to a spectroanalyser which isolates the spectral components of the signal. The spin dynamics isolates the circular components in the linearly polarized magnetic field since it reacts to them in a fundamentally different manner.

in pulse is determined by the commutator $\frac{i}{\hbar}[eA_0, \mathbf{p}] = -\frac{i}{\hbar}eA_{0,i} = -e\mathbf{E}$ which in the one-dimensional case gives $-eE_3$. There is sufficient arbitrariness in the choice of the component E_3 for it not to depend on x and y. Then $\mathbf{E}$ is a "good" operator, since it does not derive from a host of one-dimensional functions. At the same time, for one-dimensional movement along the z axis change in the pulse through the action of the potential $\mathbf{A}$ is determined by the commutator

$$\frac{i}{\hbar}[H_{pA}, \mathbf{p}] = \frac{e^2}{mc^2}A^i A_{i,3},$$

i.e. generally speaking, depends on all the $\mathbf{A}$ components. It is impossible to construct $\mathbf{A}$ so that the last commutator would not depend on x and y and at the same time correspond to the chosen calibration and the field $\boldsymbol{H}$. Thus, the potential $\mathbf{A}$ and the scalar $\mathbf{A}^2$ are operators not determined in the space of one-dimensional wave functions.

The term of the Hamiltonian (4) $\sim \mathbf{A}^2$ is sometimes simply omitted having regard to its relative smallness as compared with the term $\sim \mathbf{Ap}$. Let us use the same procedure here. In the one-dimensional case, however, the term $\sim \mathbf{Ap}$ with choice of $\mathbf{A}$ in the form of (9) makes no contribution at all to change in the pulse: $\mathbf{Ap} = 0$ and the commutator (5) is also equal to zero. For this reason the spin–orbital interaction in the model is actually the sole factor determining change in the translational energy of the proton in the magnetic field. At the same time, it is interesting to compare the evaluation of the power of conversion of spin to orbital energy with a certain reference corresponding to direct conversion of the energy of the magnetic field to the energy of orbital motion. As such a reference we shall use the evaluation of the quantum limit of the power of energy absorption of the magnetic field by a classical particle moving over a microscopic closed trajectory.

Instead of (4) taking into account (8), (9) and (10) let us write

$$\boldsymbol{H} = \frac{\mathbf{p}^2}{2m} + \boldsymbol{H}_{sH} + \boldsymbol{H}_{sh} + \boldsymbol{H}_{spr}, \tag{11}$$

where $\boldsymbol{H}_{sH} + \boldsymbol{H}_s h = -\mu\sigma\mathbf{H}$ and

$$\boldsymbol{H}_{sH} = \mu H \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \quad \boldsymbol{H}_{sh} = -\mu(\sigma^1 H_1 + \sigma^2 H_2) = -\mu h \begin{pmatrix} 0 & e^{-i\omega t} \\ e^{i\omega t} & 0 \end{pmatrix}.$$

The operator $\boldsymbol{H}_s h$ induces transitions in the spin components of the spinor wave function of the particle leaving unchanged its orbital part. The operator $\boldsymbol{H}_{spr}$ ensures transfer of energy from the spin subsystem to the orbital. To evaluate the order of magnitude of the mean value of the derivative $\mathbf{p}^2$, it is, of course, not necessary to know the exact wave functions — solutions of the Schrödinger equation with the Hamiltonian (11) since the main contribution will be made by the eigenfunctions of the prevailing term $\frac{\mathbf{p}^2}{2m}$. In addition to $\frac{\mathbf{p}^2}{2m}$, it is also necessary to allow for the term $\boldsymbol{H}_{sH}$, since part of the energy governed precisely by this term is capable of being transferred to orbital degrees of freedom, that is, it is necessary to find the eigen wave functions of the operator, $\frac{\mathbf{p}^2}{2m} + \boldsymbol{H}_{sH}$, to take a pair with different values of the energy of the spin and in these plates estimate the matrix element of the operator $\frac{i}{\hbar}[\boldsymbol{H}_{spr}, \mathbf{p}^2]$.

The eigenfunctions $\frac{\mathbf{p}^2}{2m}$ are the eigenfunctions of the pulse operator $\mathbf{p}$: $\psi_{\mathbf{p}} = e^{\frac{i}{\hbar}\mathbf{pr}}$ with the energy $\varepsilon_p = \frac{p^2}{2m}$. The eigenfunctions $\frac{\mathbf{p}^2}{2m} + \boldsymbol{H}_{sH}$ by virtue of the commutativity of $\frac{\mathbf{p}^2}{2m}$ and $\boldsymbol{H}_{sH}$ have the form $\psi_{\mathbf{p}^s} = \psi_{\mathbf{p}}\psi_s$, $s = 1, 2$ where the ψ_s values are defined in (2). We shall use the functions of one-dimensional motion $\psi_{\mathbf{p}^s} = \psi_P\psi_s$, $\psi_P = e^{\frac{i}{\hbar}pz}$. Let us find the following matrix elements using (7)

$$g_{qs} = \langle \psi_{P'q} \left| \frac{i}{\hbar}[\boldsymbol{H}_{spr}, \mathbf{p}^2] \right| \psi_{ps} \rangle = \frac{i\mu^2}{e\hbar^2} e^{ijk} \langle \psi_q | \sigma_k | \psi_s \rangle \langle \psi_{P'} | (E'_{i,l} + 2E_{i,l}p^l)p_j | \psi_P \rangle. \tag{12}$$

Allowing for the explicit form of the Pauli matrices in the basics ψ_s, we find

$$\langle \psi_q \mid \sigma_k \mid \psi_s \rangle = \begin{cases} 1 & k = 1 \\ i\theta_s & k = 2, \\ 0 & k = 3 \end{cases} \quad \theta_1 = 1, \quad \theta_2 = -1, \quad \langle \psi_s | \sigma_k | \psi_s \rangle = \begin{cases} 0 & k = 1,2 \\ \theta_s & k = 3. \end{cases} \tag{13}$$

From this it is clear that $g_{ss} = 0$, i.e. the power of the transition, is equal to zero if the spin state does not change. Substituting (13) and (10) into (12), putting for brevity $p_3 \equiv p$, we obtain

$$g_{qs} = \frac{\mu^2}{e\hbar} E'\xi(\theta_s\hbar\xi \langle \psi_{p'} | e^{i\theta_s\xi z} p | \psi_p \rangle + 2\langle \psi_{p'} | e^{i\theta_s\xi z} p^2 | \psi_p \rangle)(1 - \delta_{qs}) =$$

$$= \frac{\mu^2}{e\hbar} E'\xi p(\theta_s\hbar\xi + 2p)\delta\left(\frac{p - p' + \theta_s\hbar\xi}{2\pi\hbar}\right)(1 - \delta_{qs}).$$

Here normalization of the functions ψ_p to the δ-function is used, δ_{qs} is the Kronecker symbol. Since the real (close to minimal) values of p in the ion channel

$$p \sim \frac{\hbar}{n\lambda} = \frac{\hbar\xi}{2\pi n}, \text{ where } \lambda = 2\frac{\pi}{\xi}, \; n \sim 10, \tag{14}$$

then the term $2p$ in round brackets may be disregarded.

Because of normalization of the δ-function g_{qs} has the meaning of the density of power of the transition relating to the single interval $\frac{p'}{2\pi\hbar}$ of the final state. To obtain the power of the transition G, it is necessary to integrate the expression obtained

$$G_{qs} = \int_{-\infty}^{\infty} g_{qs} \frac{dp'}{2\pi\hbar} = \frac{\mu^2}{e} E'\xi^2 p\theta_s(1 - \delta_{qs}). \tag{15}$$

Using relations (14) and $E \sim e\left(\frac{1}{2}\lambda\right)^{-2}$ in (15), we find the evaluation of the power of the transition

$$G = \frac{\hbar(4\pi\mu)^2}{n\lambda^5} \approx 10^{-11} \text{ erg}\cdot\text{s}^{-1}, \tag{16}$$

where the pitch of the protein helix is taken as equal to 5 Å.

The evaluation obtained characterizes the rate of energy transfer of the spin to the energy of translational movement. Now let us find the rate of conversion of the energy of the magnetic field to the energy of the spin. To the latter corresponds the operator $H_{sA} = -\mu\sigma\mathbf{H}$. The power operator is equal to

$$\dot{\boldsymbol{H}}_{sA} = \frac{\partial H_{sA}}{\partial t} = -\mu\sigma\dot{\mathbf{H}}, \tag{17}$$

since $\boldsymbol{H}_{sA}$ commutates with the Hamiltonian (4). (Here evidently it is not necessary to allow for $\boldsymbol{H}_{spr}$.) From (17) we find the matrix elements of G using (8), (13)

$$G_{qs} = \psi_q | \dot{H}_{sA} | \psi_s = -\mu \langle \psi_q | \sigma_k | \psi_s \rangle \dot{H}^k = -\mu h \omega i \theta_s e^{i\theta_s \omega t}.$$

The evaluation of power corresponds to the amplitude of the matrix elements. Taking $\omega = \frac{1}{\hbar}\gamma H$ (NMR condition), $h \sim H \sim 0.5$ gauss we get

$$G = \mu h \omega \approx \frac{2}{\hbar}\mu^2 H^2 \sim 10^{-19} \text{ erg} \cdot \text{s}^{-1}. \tag{18}$$

From comparison of (18) and (19) it will be seen that the stage of transformation of the energy of the magnetic field to spin energy limits the rate of the whole process of transfer of the energy of the magnetic field through spin into translational movement.

From this it follows that in conditions of a comparatively strong non-uniform intramolecular electric field the magnetic field is connected with the spin much more weakly than the spin with the orbital degrees of freedom. Therefore, if one speaks of the resonance conversion of the energy of the magnetic field to the energy of the orbital degrees of freedom, then the frequencies of the resonances are associated rather with the parameters of the orbital motion of the particle than with the NMR frequencies. Calculation of such resonances in models of specific biophysical systems is a problem in its own right.

Finally, let us find for comparison the scale of the power of the process of the direct conversion of the energy of the magnetic field to orbital motion described by the equation

$$m\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -e\,\mathrm{grad}A_0 - \frac{e\partial \mathbf{A}}{c\partial t} + \frac{e}{c}\,[\mathbf{v}\ \mathrm{rot}\mathbf{A}]. \tag{19}$$

The instant power is determined by the expression $G_t = e\mathbf{vE}$ following from (19). We are interested in the component $\mathbf{E}$ induced by the alternating magnetic field. Two factors are fundamental in this regard. Firstly, for laboratory magnetic fields the upper evaluation of the modulus $\mathbf{E}$ is determined by the formula $E \sim \frac{R}{2c}\left|\frac{\mathrm{d}H}{\mathrm{d}t}\right|$, where R denotes the characteristic dimensions of the magnetic field source. However, the size of the region of movement of the particle potentially responsible for biomagnetism is much smaller than R. In addition, the particle may acquire and lose energy on different parts of the pathway. In such a case it is sensible to evaluate the mean power for a certain interval of microscopic motion. Secondly, for remote magnetic field sources such as the geomagnetic field or a field of industrial origin, only the circulation rot $\mathbf{E}$ and not the field $\mathbf{E}$ itself is determined. Therefore, there are sufficient grounds for considering the power of the process of energy conversion in relation to the finite motion of the particle and of using the approximation of a closed trajectory.

Let the particle move over a closed contour C of length L perpendicular to $\mathbf{H}$. The power average for the period of movement is determined by the contour integration of G_t. Using the Stokes' theorem and the condition of uniformity of the magnetic field, we get

$$G_c = \frac{e}{L}\oint_C \nu \mathbf{E}\mathrm{d}\mathbf{l} \leqslant \frac{ev_m}{L}\int_s \mathrm{rot}\mathbf{E}\mathrm{d}\mathbf{s} = -\frac{ev_m}{cL}\int_s \frac{\mathrm{d}\mathbf{H}}{\mathrm{d}t}\mathrm{d}\mathbf{s} \leqslant \frac{e}{2c}v_m r\left(\frac{\mathrm{d}H}{\mathrm{d}t}\right)_{\mathrm{ampl}},$$

where s is the area of the contour, r is the radius of the circumference described about the contour, $\nu = |\mathbf{v}|$, ν_m is the maximum speed of the particle in the period of movement, $\left(\frac{\mathrm{d}H}{\mathrm{d}t}\right)_{\mathrm{ampl}}$ is the amplitude value of $\frac{\mathrm{d}H}{\mathrm{d}t}$, and $H = |\mathbf{H}|$.

If $H \sim \sin \omega t$ then G_c may be written as

$$G_c \leqslant \frac{e}{2c} vrH\omega = \frac{e}{2c}\frac{pr}{m}H\omega, \tag{20}$$

where ν_m is replaced by ν. However, G_c cannot be arbitrarily small because of quantum effects.

Noting that $\mu = \mu_r\mu_N = \mu_r \frac{e\hbar}{2mc}$, where μ_r is the relative magnetic moment, we obtain from (20) and (18) the power ratio by indirect (via spin) and direct mechanisms

$$\frac{G}{G_c} \sim \mu_r \frac{\hbar}{pr}. \tag{21}$$

In fact, it is equal to the ratio of the spin and orbital angular moments of the particle.

Many models of biomagnetic effects are based on analysis of the dynamics of small ions moving in confined microscopic areas well protected from the thermal oscillations of the medium [29]. In this case it is justified to evaluate the orbital moment of the pulse of the particle pr from the generalized relation of indeterminacy, which in the corresponding system of coordinates links the indeterminacy of moment with that of the angular coordinate: $\Delta(pr)\Delta\varphi \geqslant \frac{1}{2}|\langle i[l, \varphi]\rangle|$ where $l = -i\hbar\frac{\partial}{\partial}\varphi$ and φ is the operator of the angular moment and the angular coordinate, and r is the size of the region of movement of the particle, for example, the size of the ion channel. Since $\Delta\varphi \sim 2\pi$, then

$$\frac{G}{G_c} \leqslant 4\pi\mu_r \approx 36$$

for the proton. Similar evaluations for such biochemically important ions as ^{39}K, ^{23}Na and ^{35}Cl give the values (with reference to their mass) $\frac{G}{G_c} \approx 64$, 214 and 120. However, for example, ^{40}Ca and ^{24}Mg ions have a zero nuclear spin and their motion is unrelated to spin. However, it should be noted that in most experimental studies with recording of calcium ions in biological systems in the magnetic field use has been made of the ^{45}Ca isotope [16] for which the ratio $\frac{G}{G_c}$ also amounts to a few tens.

The evaluations obtained show that when the power of the direct conversion of the energy of the magnetic field to orbital energy approaches its quantum limit, the spin degrees of freedom begin to play a crucial role.

CONCLUSION

Only 10–20 years ago a biological action of low-frequency low-intensity magnetic fields appeared impossible, since the field power is insufficient for any serious heating of the tissues and a quantum of the field energy, in turn, has a value many orders less than kT. Today a host of evidence has been gathered indicating the biological efficacy of both weak e.m.f. and magnetic fields and agents of a material nature — solutions of preparations in extremely low concentrations [30].

The view is generally accepted that very minor changes induced by weak external agents in the dynamics of particles forming living tissue are capable of being enhanced through irreversible processes of metabolism. Diverse and potent buffer systems which usually protect the body from the action of external stimuli turn out to be excluded. The effect of weak factors lies below the

threshold of actuation of buffer systems and accumulates at sub-buffer level on prolonged exposure (tens of minutes and longer).

There is no doubt that only allowance for the functioning of biophysical structures in regimes far from equilibrium offers the possibility, in principle, of explaining the phenomenon of low doses and weak influences. In relation to non-equilibrium structures the concept of temperature and together with it that of the mean energy per degree of freedom kT has an essentially limited meaning. In particular, the concept of temperature is inapplicable to the ensembles of biophysical structures which possess the property of staying in long-lived or metastable states the relaxation of which is impeded in one way or another. (For example, the metastable states of an aqueous solution of glycyl tryptophan induced by an external magnetic field relax in about 2 h [31].) For an adequate comparison of the parameters of such structures other energy scales differing from kT are necessary.

In this work we have made use of the fact that two different modes of conversion of the energy of the magnetic field to the dynamics of a particle exclude any further possibilities. Therefore, a relative estimation of the power of these processes makes sense. It is interesting that it substantially validates the thesis on the participation of nuclear spin degrees of freedom in biochemical processes.

If the nature of the biological action of weak low-frequency magnetic fields is connected with absorption of the energy of the magnetic field, then in relation to the initial stage of the mechanism of reception of the magnetic field the following propositions are valid. There exist, as stated, two modes of conversion of the energy of the magnetic field to the energy of the orbital degrees of freedom of particles which in the final analysis control the biochemical processes. These are (1) direct conversion by a mechanism allowing of the classical analogy; and (2) indirect conversion with the participation of spin degrees of freedom of the particles. The power of the direct process approaches the quantum limit when the pulse of the particles is sufficiently small and does not satisfy the relation $p >> \frac{\hbar}{r}$, where r is the size of the region of movement. This occurs in confined areas of biophysical systems sufficiently protected from the environment. At such sites, which are often key for biochemical reactions, the nuclear spins become an essential factor. If the biochemically significant motion of a particle is quasi-unidimensional, then the role of the nuclear spin becomes predominant.

Since the sub-integral expression in (15) contains a δ-function of the difference $p - p' + \theta_s \hbar\xi$ the bulk of the power is provided by the transitions to the state $p' = p + \theta_s \hbar\xi$. In this connection we note the following

(1) The value of $\hbar\xi$, $\xi = 2\pi\lambda^{-1}$, λ is the pitch of the helix of about 5 Å, corresponds to the energy of the proton in the e.h.f. range of about 10^2–10^3 GHz. The pumping of such a mode of the proton judging from numerous experimental data in the region of the biological action of the e.m.f. in the e.h.f. range may prove important for biochemical processes. Pumping is real given the metastability of the states of the particle in the ion channel, i.e. the difficulty of thermal relaxation of these states; in [7] the protein helix of the channel is regarded as an effective insulator of external thermal oscillations.

(2) Asymmetry of p' exists in relation to the forward $s \to q$ and back $q \to s$ transitions and in relation to the right $\xi = |\xi|$ and left $\xi = -|\xi|$ twisting of the protein helix. It is assumed that the chirality factor of the helix interferes with the asymmetry of spin dynamics in relation to the right $\omega = |\omega|$ and left $\omega = -|\omega|$ rotations of the magnetic field so that if the mechanisms considered exist they will be observed only for one type of enantiomers of the protein helices regardless of

the direction of the constant and direction of the rotation of the alternating magnetic field components.

Note that relation (21) links the powers of the "spin" and direct mechanisms irrespective of whether NMR conditions are met. It would be wrong, therefore, to consider that the mechanism of the pumping of orbital energy through spin is a development of the NMR idea. For example, one cannot say beforehand that the frequencies of the possible "spin–orbital resonances" will somehow correlate with the NMR frequencies even in order of magnitude. These resonances, unlike NMR, depend not only on the magnetic moment of the particle and the size of the field, but also on the specific structure of the region of motion of the particle.

Now it is possible to answer the question on which process might serve as detector of the nuclear spin dynamics instead of the absorption signal of the energy of the magnetic field. This is a biochemical process part of the model of which is the dynamics of spin particles within the "active centre". It must be expected that the rate of the process amenable to measurement will experience resonance change in accord with resonance in the conversion of the energy of the magnetic field to the energy of orbital motion.

Recently, considerable results have been achieved in a traditional scientific direction of geometrization of physical fields. Apparently it has been possible to construct a space of events in which all currently known physical fields and interactions are described in one way [32]. The central object of the new non-linear theory is provided by so-called fields of inertia or torsional fields. Mathematically, they represent tensor fields and are closely linked with the property of twisting of space. The Schrödinger equation appears in this theory as a certain linear approximation with no theoretical restrictions on the value of the non-linear effects. The parameters of the theory in this respect must be established experimentally. In addition, the fields of twisting themselves are generated, in particular, by the spins of the microparticles. In this connection it is interesting to assume that the interaction or interference of the rotating magnetic field, spin and helical electric field admits of effects not described by equation (3) regardless of the magnetic moment of the particle but are "genetically" determined by the spin.

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