Magnetic biominerals localised in brain tissue: anomalous properties, possible functional role and synthetic analogues

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Abstract

Anomalous properties of biogenic magnetic minerals localised in human and animal brain tissues are described. The experiments are performed using a ferrimagnetic resonance technique. It is shown that the ferrimagnetic resonance signals caused by physiogenic and pathogenic magnetic biominerals can be detected in the brain tissues. When the microwave power exceeds a critical value (~ 80 mW), physiogenic magnetically ordered nanoparticles demonstrate a presence of unique dynamic effects. To our opinion, these effects are associated with transitions of the biogenic magnetic nanoparticles to macroscopic quantum states, which manifest themselves at the room temperature. It is supposed that the physiogenic magnetic biominerals play an important role in the brain functions, while the pathogenic biominerals cause brain diseases. We describe the main principles for development of technologies aimed at creation of synthetic materials with the macroscopic quantum effects occurring at the room temperature. Possible applications of our results for solution of fundamental and applied problems are analysed.

Keywords: magnetic biominerals, ferrimagnetic resonance, brain, nanoparticles

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1. Introduction

The interest in biomineralogy, which studies minerals of biological origin, has rapidly grown in the recent years, since this field offers new prospects when solving different mineralogical, medical and technological problems [1– 5]. At present, over 50 types of inorganic crystalline particles, known as biominerals, have been discovered in the human organism [3 – 5]. For the most part, investigations in the field of biomineralogy are connected with studies for biominerals localised in highly mineralised biological tissues (tooth enamel, bones, etc.). However, biomineralisation processes are quite universal. Inorganic mineral inclusions are also formed in many weakly mineralised biological tissues [6–10]. Among different types of biominerals, magnetic mineral particles localised in the brain and other weakly mineralised tissues are the most interesting for us.

Investigations of mineral inclusions in weakly mineralised tissues are difficult for many reasons. One of them is associated with the fact that mineral particles occupy a very small volume in the weakly mineralised tissues. This makes it difficult to look for the mineral particles or to prepare samples under test. At the same time, a presence of mineral inclusions in weakly mineralised tissues, including the brain tissue, is a well-established experimental fact. Availability of magnetic biominerals in the brain tissue has been confirmed with electron microscopy, electron diffraction, magnetic resonance and other techniques [7, 11]. As a rule, magnetically ordered nanoparticles localised in the brain tissues and often called as "biomagnetites" are in fact complex multiphase compounds based on iron oxides and hydroxides [7, 12].

Functional role of the magnetic biominerals localised in the brain tissue still remains debatable [6, 11, 12]. A lot of suppositions about the importance of biomagnetites in navigation of birds, fish and other living organisms have been put forth [11]. A possible role of physiogenic biominerals in the brain function and relations of pathogenic biominerals to brain diseases have been discussed, too [6–9]. However, the functional role of the biomagnetite has been proven experimentally only for some bacteria, which move along magnetic force lines [7, 13].

The results related to studies of brain and other weakly mineralised biological tissues with the magnetic resonance spectroscopy have been reported in many works (see [6, 8–10, 14–19]). So, the works [6, 8, 9, 16–18] describe the effect linked to splitting of the resonance signals at high levels of the microwave power. These resonance signals have been described in the most of studies as electron paramagnetic resonance (EPR) signals. At the same time, the resonance signals under consideration should be attributed to ferrimagnetic resonance (FMR) [20], according to the works [6, 17, 18]. The experimental data concerned with anisotropy of the FMR signals and influence of strong microwave fields on their shape have been reported in the studies [6, 8, 9].

In spite of much research devoted to the magnetic biominerals, the properties of the latter are insufficiently understood, in particular when it comes to formation mechanisms, functional role and different physical characteristics. The influence of microwave power on the shape of the FMR spectra and the interpretation of this physical phenomenon requires further investigations. In addition, the technologies for creating synthetic analogues of the magnetic biominerals also remain poorly developed.

The goals of this work are related to studies of anomalous properties of the magnetic biominerals on the basis of the FMR, analysis of a functional role of these biogenic minerals, and development of technologies for creating synthetic materials, which would possess specific properties of naturally occurring magnetic biominerals. Finally, possible applications of the obtained results for solving various medico-biological and technical problems are also discussed.

2. Sample preparation and experimental methods

Our experiments were performed on human and animal (rats) brain tissues and on the samples extracted from shells of molluscs (*sacciena putris*, *unio ristorum*, and *lymnaea stangalis*). The human and animal brain tissues were obtained from the Kiev Institute of Neurosurgery (Ukraine) and the Kiev Institute of Biochemistry (Ukraine), respectively. In the case of mollusc shells, the experiments were performed on the organic matter covering exterior of the shells. Measures were taken to prevent contamination of samples by magnetic materials during the preparation process.

The experiments were carried out using an EPR spectrometer PS-100.X (Belarus), which operated in the three-centimetre wavelength range (an X-band). The maximal microwave power of the spectrometer was approximately equal to 100 mW and the frequency of its modulating magnetic field was 100 kHz. The main experiments were performed at the room temperature. A standard sample $CuSO_4 \cdot 5H_2O$ was used while analysing the resonance signal intensities.

3. Experimental results and discussion

3.1. General characteristics of the resonance signals

Several types of resonance signals with different linewidths ΔB have been detected for the samples under study. We have divided these signals into the two following groups: the first one for the narrow signals (with $\Delta B \sim 5-8$ mT), and the second for the broad signals ($\Delta B \sim 15-150$ mT). The typical shape of the narrow signals is presented in Fig. 1. These signals could be detected in both human and animal brains, in organic component of the mollusc shells and other biological tissues.

A comparison of signal intensities for different samples of the brain tissues have shown that the narrow signals, as a rule, have lower peak intensities than the broad ones. Then the volume of the areas producing the broad signals must be larger than that of the areas giving rise to the narrow signals. Let us suppose that these signals are caused by the EPR. Then the local concentration of paramagnetic centres would have to be higher than 10^{22} spin/gr. Such high concentrations are atypical for the paramagnetic ions present in biological tissues. As a consequence, one can conclude that the resonance signals in the brain tissues, as well as in other samples studied by us, should be caused by magnetically ordered mineral inclusions and so those signals can be related to the FMR.

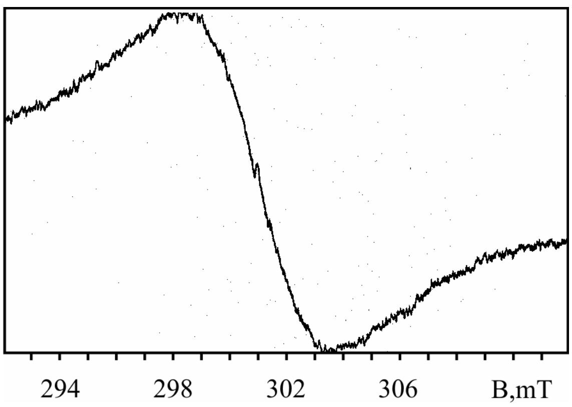

Fig. 1. Shape of narrow resonance signal for the microwave power P smaller than the critical value ($P < P_{cr}$). Attenuation of the microwave power is equal to 1.76 dB. The abscissa corresponds to linear scan of the static magnetic field.

It is important that the appearance of both the narrow and broad signals in our samples does not have a systematic character. In the most of cases, the resonance signals are absent in fresh samples. However, if the resonance signals do appear later in a given sample, they would remain stable in time. The reasons explaining the presence (or absence) of the resonance signals may be as follows. Basing on the experimental data, it is reasonable to assume that the brain tissue contains iron hydroxides and oxides. Since the brain tissues reveal no magnetic resonance signals immediately after extraction from an organism, their mineral particles should be initially in the antiferromagnetic or paramagnetic states rather than the ferrimagnetic state.

The magnetic characteristics of the iron hydroxides and oxides are now well-known [11]. At the room temperature goethite, α-FeO(OH), has an antiferromagnetic order, while acaganeite, β-FeO(OH), reveals a phase transition from antiferromagnetic to paramagnetic state at $T \approx 22$ °C, which is close to the physiological temperature (37 °C). Notice that the phase transition temperature depends on the size and shape of nanoparticles. Hematite, α-Fe_2O_3, has an antiferromagnetic (or weakly ferrimagnetic) order at the room temperature, whereas both magnetite, Fe_3O_4, and maghemite, γ-Fe_2O_3, reveal a ferrimagnetic order. The magnetic state of ferrihydrite, $5Fe_2O_3{\cdot}9H_2O$, is caused by many factors linked to degree of hydratation and hydroxylation of the nanoparticles. Finally, the magnetic state of ferritin (a protein containing iron) depends on different factors.

One can readily suppose that the resonance signals observed by us are most likely caused by ferrimagnetic biominerals such as the magnetite Fe_3O_4 and the maghemite γ-Fe_2O_3, or by the ferritin. A confusing appearance of the resonance signals in the brain tissues may be explained as follows. The initial samples of the brain tissue contain iron biominerals in their antiferromagnetic or paramagnetic states but the ferrimagnetic biominerals (e.g., the magnetite and the maghemite) should be absent there. During the sample preparation, the iron hydroxides and oxides in the brain samples can pass from the antiferromagnetic or paramagnetic states to the ferrimagnetic one, owing to dehydratation and dehydroxylation processes. Since the sizes of the magnetic mineral particles localised in the brain tissue remain in the nanoscale range, the nanoparticles can stay in superparamagnetic, single-domain or pseudo-single domain states.

The areas that produce the resonance signals are distributed inhomogeneously in the samples. As a rule, cutting of samples revealing the resonance signals into two parts yields in the absence of any signal in one part and the same signal in the other part. Therefore we conclude that the biological tissues under study should have small specific areas which produce the resonance signals. The volume of these areas should be very small when compare with the total volume of the sample.

The experiments have proven similar spectroscopic and dynamic characteristics of the narrow resonance signals occurred in different biological tissues (human and animal brains, organic matter from the exterior side of mollusc shells, etc.) and in different samples of the same tissue. Nonetheless, the characteristics of the broad signals in different tissues and different samples differ substantially. As a result, (i) the biological tissues under study have special areas where the mineral particles produce the resonance signals with similar characteristics. We suppose that these mineral particles are physiogenic biominerals and, moreover, formation of these biominerals in the living organisms is programmed on the level of genes. On the other hand, (ii) the biological tissues also have the areas where magnetically ordered particles have essentially different characteristics. These mineral particles represent nothing but pathogenic biominerals, of which formation is caused by some transformation of physiogenic processes into pathogenic ones.

The narrow signals presented in Fig. 1 are essentially anisotropic. When the samples are rotated in the microwave cavity, substantial changes in the resonance field B_{res} occur. Then the effective factor of spectroscopic splitting g_{ef} changes within the range of 1.83–2.24 (at the room temperature) [9]. Basing on the experimental data [9], one can draw a conclusion that the narrow signals are caused by a large quantity of magnetic particles with the same or similar orientations. Issuing from essential anisotropy of the resonance signals, one can also conclude that the biological tissues have special needle-shaped areas. The magnetically ordered particles are localised in (or associated with) those areas. It would be reasonable to assume that a role of needle-shaped structural units in the biological tissues is played by axons of neurons, different fibrillar proteins, and other textured biological tissues.

It is important to mark that the sample rotation in the 0−180° range gives rise to four extrema in the angular dependence of the narrow signal [9], while the resonance fields B_{res} of the signal are essentially temperature-depend. Almost a linear increase in g_{ef} (and accordingly, decrease in B_{res}) takes place with decreasing temperature [6, 9, 16−18]. In the temperature range of 77−300 K (at a fixed sample orientation in the magnetic field), the effective factor of spectroscopic splitting g_{ef} can change its value from 2.28 to 2.08 [9]. Since the characteristics mentioned above are not typical for the EPR signals, we have additional arguments favouring that the resonance signals are produced by just magnetically ordered particles.

Thus, the resonance signals studied by us are not associated with the EPR and, accordingly, the signals are not caused by paramagnetic ions lacking magnetic ordering. The signals are rather due to the ferromagnetic resonance or the FMR, being caused by some magnetically ordered mineral (inorganic) particles localised in the organic biological tissues.

3.2. Macroscopic quantum effects at room temperature

The narrow signals demonstrate a presence of unique dynamic effects. If the power of the microwave field becomes larger than a critical value P_{cr} ($P > P_{cr}$), additional lines appear on the contour of the initial resonance signals (Fig. 2). For different samples and different orientations, the critical microwave power P_{cr} determined at the room temperature acquires the values in the interval 65−85 mW. Increasing microwave power leads to increase in the quantity of the additional lines (see Fig. 2). It is worthwhile that phases of the additional lines and the initial signal are opposite (Fig. 2). Moreover, appearance of

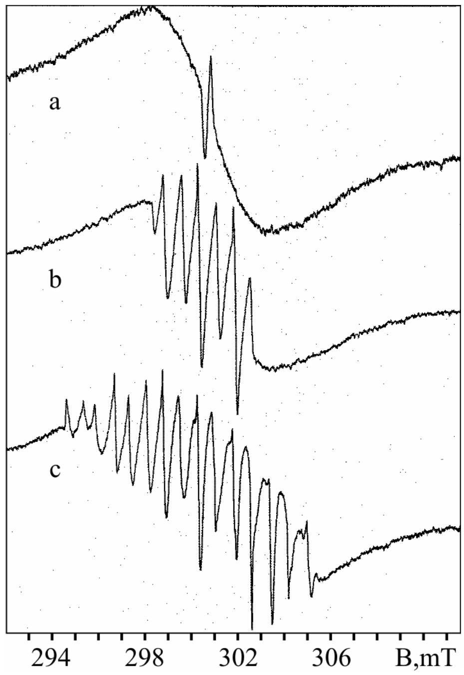

Fig. 2. Shape of narrow resonance signals for the microwave power *P* greater than the critical value ($P > P_{cr}$). Attenuation of the microwave power for curves *a*, *b* and *c* is equal to 1.75, 1.20 and 0.00 dB, respectively.

the additional lines is sensitive to the temperature of samples. The critical microwave power diminishes if the samples are slightly (by several degrees) heated [6, 16–18].

Some characteristics of the additional lines are illustrated in Fig. 3. Fig. 3a shows a narrow resonance spectrum, with the additional lines present. The spectrum displayed in Fig. 3b corresponds to a fragment of the spectrum which is marked by vertical lines in Fig. 3a. The width of this fragment is approximately equal to 5.5 mT. The spectrum shown in Fig. 3c has been obtained by computer integration of that presented in Fig. 3b. Finally, the spectrum of Fig. 3d, with the width close to 2 mT, corresponds to the fragment marked by vertical lines in Fig. 3b.

The spectrum of Fig. 3b has two approximately linear sections, short and long ones. The width of the former tends to zero as the amplitude of the modulating magnetic field decreases. This is why transition among different long sections is a jump-like process. Integration of the long (nearly linear) sections results in appearance of approximately parabolic zones on the contour of the initial resonance signals (see Fig. 3c). The widths of different parabolic zones are nearly equal, with each individual zone about 1.6 mT wide. Therefore, the number of parabolic zones increases if the microwave power does (Fig. 2), though the widths of the individual zones remain approximately equal (see Fig. 3).

It is also worth mentioning that the microwave power absorption in the region of the parabolic zones under the condition $P > P_{cr}$ is less than that for the case of $P < P_{cr}$. Reduction of the microwave power absorption at $P > P_{cr}$ is illustrated in Fig. 2. The phase of the additional lines is opposite to that of the initial signal. In other words, absorption of the microwave energy decreases in the areas of parabolic zones. This fact may be caused either by reduced magnetic moment of the sample (magnetisation at the resonance frequency) or by generation of the microwave energy by magnetic nanoparticles.

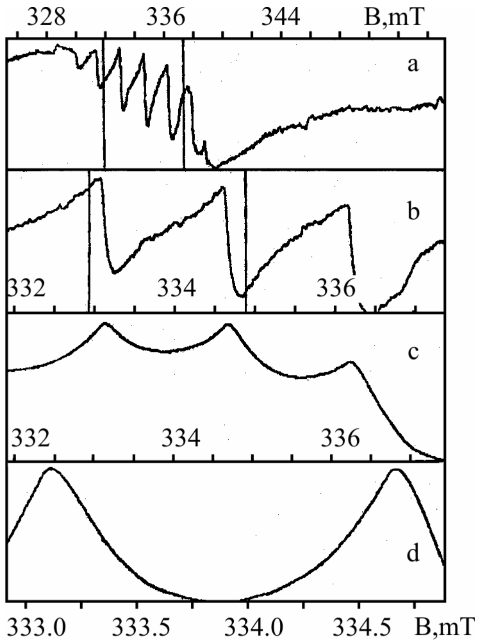

Fig. 3. Processing of experimental spectra: signals *a* and *b* are first derivatives of the absorption lines, while signals *c* and *d* are obtained by computer integration of the experimental spectra.

A possible generation of microwaves is illustrated in a more detail in Fig. 4. It is well-known that the EPR spectrometers detect the first derivative of the absorption lines. As a result, the spectra presented in Fig. 1, Fig. 2, Fig. 3a and Fig. 3b are the first derivatives of the appropriate absorption lines. Besides, the dynamic effects under discussion may be illustrated more visually by means of the initial absorption lines. Fig. 4a and Fig. 4b show the absorption lines corresponding to $P < P_{cr}$ and $P > P_{cr}$, respectively. The absorption lines have been obtained by computer integration of the appropriate experimental spectra. The difference of the two absorption lines is presented in Fig. 4c. In other terms, Fig. 4c displays a dependence of the magnetic moment (the difference of microwave magnetisation) of sample, or the intensity of microwave generation, versus the linear scanning of the static magnetic field.

The occurrence of the additional lines has a threshold character. The spectra presented in Fig. 1 and Fig. 2a have been detected under identical conditions, except for the power of the microwave field. The microwave power attenuation in Fig. 2a has been decreased only by 0.01 dB, when compare with Fig. 1 (i.e., the microwave power has been 2.3 per cent larger). However, this very small increase of the microwave power has resulted in appearance of an intense additional line (see Fig. 2a).

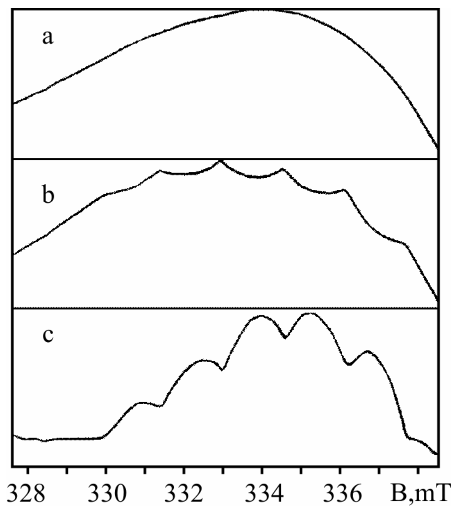

Fig. 4. Absorption lines versus linear scanning of the static magnetic field. Curves *a* and *b* are obtained by computer integration of the experimental spectra at $P < P_{cr}$ and $P > P_{cr}$, respectively, and curve *c* is a difference of the absorption curves *a* and *b*.

As already mentioned above, the quantity of the additional lines increases with increasing microwave power (Fig. 2). Hereafter we will use the symbol B_1^0 for labelling the region of linear scanning of the static magnetic field where the additional lines appear. The dependence of B_1^0 on the microwave power is presented in Fig. 5. Because the appearance of the first, second, etc. parabolic zones has a threshold character and the distance between the centres of the neighbouring zones amounts to 1.6 mT, the solid line shown in Fig. 5 is merely approximation of a step function. Nonetheless, one can consider that the dependence of the B_1^0 parameter on the microwave power is roughly linear.

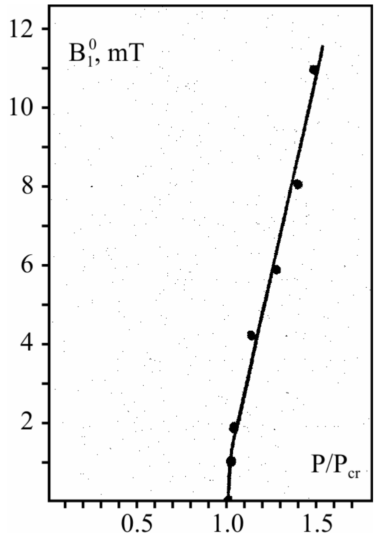

Fig. 5. Dependence of linear scanning interval for the static magnetic field B_1^0, where the additional lines appear, on ratio of the microwave power P to its critical value P_{cr}.

Basing on the experimental data mentioned above, one can conclude that the strong resonance microwave fields ($P > P_{cr}$) stimulate a phase transition in the magnetic particles and transfer those nanoparticles into a new specific state. The most important characteristics of the transition (and the new state) are the following: (i) a threshold character of the dynamic effect (see Fig. 1, Fig. 2a and Fig. 5), (ii) jump-like processes on the boundary of the parabolic zones (see Fig. 3), (iii) a specific dependence of the magnetic moment (microwave magnetisation) or the microwave field generation upon the linear scan of the static magnetic field (see Fig. 4), and (iv) an increase in the quantity of parabolic zones (or additional lines) occurring with increasing microwave power (see Fig. 2 and Fig. 5). The characteristics of the dynamic effects listed above are similar to those of the effects associated with macroscopic quantum states in superconducting materials and, in particular, in Josephson junctions [21–23].

Hence, comparison of the dynamic effects with the behaviour of substances staying in the macroscopic quantum states provides some grounds for the assumption regarding stimulation, by a strong microwave field, of transition of the biogenic magnetic nanoparticles into a macroscopic quantum state. If the assumption is indeed correct, then the hybrid organic-mineral nanosystems localised in the brain tissue should demonstrate unique properties, namely, macroscopic quantum effects at the room temperature.

At present there is no theory which could clearly explain the features observed in the FMR spectra. Qualitative interpretation of mechanisms of the effects can be conducted in the framework of different models. These models have to take into account nonlinear effects involved in the FMR. A strong resonance microwave field increases concentration of magnons (spin waves) inside individual magnetic nanoparticles and so stimulates magnon-magnon interactions. The magnon pairs and specific multi-magnon systems can form nanoparticles. That is why we believe that the magnon concentration and magnon-magnon interaction are essentially involved in the dynamic effects occurring at high microwave power levels. Beside of the precession caused by linear scan of the static magnetic field, precession (oscillation) of the magnetic moment of multi-magnon systems formed by interconnected magnons can also be of significance in the dynamic effects. Interdependence of the oscillations of these two types, due to modulation effects, can matter much in the transformations observed in the FMR spectra.

Interactions among the neighbouring magnetic nanoparticles can also be of importance in the dynamic effects. Phonon-induced tunnelling between the neighbouring nanoparticles (under strong resonance microwave fields and, correspondingly, high concentrations of magnons) can stimulate a coherent precession of the magnetic moments of different nanoparticles. The tunnelling efficiency increases with increasing temperature, closeness of nanoparticles and concentration of magnons. The system of magnetic nanoparticles involved in this tunnelling is similar to the systems corresponding to the Josephson junctions. As a result of all the factors mentioned above, the macroscopic system of magnetic nanoparticles can pass into a coherent state.

3.3. A role of magnetic biominerals in functioning and diseases of the brain

As stressed above, formation of inorganic mineral particles in the biological tissues takes place not only in highly mineralised tissues (tooth enamel, intercellular substance of bones, and so on) but also in weakly mineralised ones. The organic matrix of bones and teeth stimulates formation of hydroxylapatite nanocrystals [3–5]. On the contrary, the brain tissues stipulate formation of iron hydroxides and oxides. The general principles of biomineralisation processes in both highly and weakly mineralised tissues are similar in many ways. In particular, pathological mineralisation may occur in the both cases, apart from a common physiological mineralisation.

It is important to notice that the properties of physiogenic biominerals are determined by the organic matrix, which governs a growth, sizes and shape of the inorganic mineral particles [3–6, 12]. The control is realised via a phenomenon called bioepitaxy, as well as the energy associated with surface of the particles. Consequently, the size of physiogenic mineral particles must be in the range of nanometres, since this is the only case when the contribution of the surface energy to the overall energy of the particle is substantial. The organic matrix and the physiogenic mineral particles form an interconnected hybrid organic-mineral nanostructural matter, or a mineral-organic nano-associated (MONA) system [24]. The structural units of the MONA systems are mineral (inorganic) nanocrystals and organic layers that cover and separate the mineral particles. These structural units of the MONA systems possess a non-equilibrium electric charge, which depends on external factors and can change in time [24]. Because the properties of the mineral (inorganic) matter in the MONA systems are determined by organic matter, the hybrid organic-mineral nanocomposites may be considered as a separate class of materials with very specific properties [6, 24].

As stated above, the brain and the other biological tissues produce the narrow ($\Delta B \sim 5{-}8$ mT) and the broad ($\Delta B \sim 15{-}150$ mT) resonance signals. The characteristics of the narrow signals in different biological tissues and different samples of the same tissue are similar. In contrast to the narrow resonance signals, the broad signals have different characteristics both for different biological tissues and different samples of the same tissue. Based on these facts, one should assume that the narrow signals are produced by normal physiological mineral particles with similar properties, whereas the broad signals originate from pathological mineral particles revealing different characteristics.

The physiological mineralisation is programmed on genetic level. At the same time, pathological biomineralisation arises due to some disruption of normal physiological biomineralisation processes. The physiological mineral particles must play some functional role in the brain tissue. On the other hand, appearance of the pathological biomineralisation leads to disruption of that function and, accordingly, to illness of the brain tissues. For instance, it is well-known that the Alzheimer’s disease correlates with increasing quantity of iron in the brain tissues [7]. Therefore understanding of biomineralisation mechanisms of the iron oxides and hydroxides would open new prospects in developing methods for prevention and treatment of brain diseases.

It would be reasonable to suppose that the physiological mineral particles play an important part in the storage and processing of information in the brain tissue. The literature describes mechanisms of the information storage and processing in the brain so that, as a rule, it is related to various organic substances and processes occurring on the level of ions [25]. However, such processes are rather slow. Therefore one can assume that, besides the slow processes mentioned above, another rapid processes are also of significance in the brain function. The rapid processes have to take place on the levels of electrons and magnetic characteristics of nanoparticles. As a consequence, an assumption appears that the magnetic states of physiological biominerals and the rapid changes of their states should be substantial in the brain function. If that function were compared to the computer systems, then the magnetic particles would have played a part of data processors. Although there are many such processors, the number of neurons is much greater, so that an extra processor must control functioning of a large number of neurons.

All the unique dynamic properties of the physiological magnetic nanoparticles described above become apparent after extraction of the samples from an organism. Nonetheless, we assume that the physiological nanoparticles have also specific properties in the living organism, i.e. in their native state. Because the FMR signals in the initial samples are absent immediately after extraction from organisms, the physiological nanoparticles should have antiferromagnetic ordering in a living organism. Most likely, these particles should be related to goethite α-FeO(OH), acaganeite β-FeO(OH), hematite α-Fe_2O_3 or ferritin. The antiferromagnetic state of the magnetic particles makes it difficult to detect the nanoparticles in the living organisms.

As shown above, the FMR signals of the brain tissue are essentially anisotropic and so must be formed by needle-shaped organic structural elements of the brain tissue. Most likely, the organic structural elements contain many magnetic nanoparticles with similar orientations. A needle-shaped organic structural element may be considered as organic matrix that stimulates mineralisation and controls the size and shape of the mineral nanoparticles, together with their magnetic properties. Then these mineral particles are typical representatives of the MONA systems, whose structural units (nanocrystals and organic layers) have a non-equilibrium electric charge depending upon external influences [24]. The surface electric charge of the nanoparticles can be formed by biopotentials produced by neurons and other biological cells.

The presence of electric charge on the surface of magnetic nanoparticles can be very important in the mechanisms of brain functioning. It is known that so-called magneto-electric effects are possible in some types of crystals [26–29]. The magnetic moment in these crystals can be changed by an electric field, while the electric polarisation by a magnetic field. The crystallographic and magnetic symmetries of the crystals would determine a possibility (or impossibility) of the most well-known (traditional) magneto-electric effect first described by Landau and Lifshitz [26]. However, inhomogeneous and surface magneto-electric effects are also possible near domain walls or surface of the magnetic particles [27, 29]. Unlike the traditional effect, such inhomogeneous and surface magneto-electric effects are not symmetry restricted [27, 29].

It is known that some bacteria demonstrate ability for moving the along magnetic field lines [13]. There are magnetic nanocrystals included inside of these bacteria, which act a magnetic compass [7, 13]. It would be natural if the magnetic signals formed inside the compass due to magnetic fields were transformed to electric signals owing to magneto-electric effects. One can also suppose that the magneto-electric effects are significant in functioning of the human and animal brains. These effects promote transformation of magnetic signals to electric ones, which can be transmitted to different neurons.

Thus, investigations of the properties of magnetic biominerals open new prospects for studying the brain functioning. We should emphasise that the mineral inclusions in the brain tissue have a structure of solid-state particles. This fact, together with the information available on the properties of nanoscaled solid-state particles, opens new possibilities for description of the processes occurring in the brain tissues by means of direct physical techniques.

3.4. Synthetic analogues of magnetic biominerals

Preparation of magnetic biomineral samples for experimental investigations is difficult because the magnetic nanoparticles occupy a very small volume in the biological tissues. Moreover, it is difficult to control the processes leading to modifications of magnetic state of the prepared samples. These factors make detailed studies of properties of the magnetic biominerals very cumbersome. In order to study the mechanisms of the macroscopic quantum effects and the role of magnetic biominerals in the brain function, it is necessary to develop technologies for creating synthetic analogues of the magnetic biominerals.

We are inclined to suppose that the optimal technologies for creation of synthetic analogues of the magnetic biominerals have to be similar to biomineralisation processes known to take part in the living organisms. The conditions associated with formation of biogenic magnetite have been described in the most detail for bacteria [30]. It is believed that the magnetite is formed by dehydratation and dehydroxylation of the iron hydroxides and the oxygen concentration strongly affects the process of magnetite biomineralisation. The results described in the works [12, 30, 31] enable one to analyse the influence of synthesis conditions on the size, phase composition and magnetic properties of the nanoparticles obtained with different technologies.

In order to create the synthetic analogues in laboratory conditions, magnetic nanoparticles must be formed in the presence of organic matrices. The matrix, together with magnetically ordered nanoparticles, must form a hybrid mineral-organic nanosystem. Basing on the results described by us, we assume that the optimal technologies for creating the synthetic analogues must include formation of iron hydroxide nanoparticles associated with the organic matrix, and subsequent transformation of these hydroxides into iron oxides. The transformation must occur owing to the processes of dehydratation and dehydroxylation, as well as additional oxidation (or reduction) of the iron ions.

Development of methods suitable for comparison of the corresponding characteristics of the synthesised material and the biogenic magnetic particles themselves is also very important for solving the problem discussed here. The most important criterions of equivalence of the synthetic hybrid organic-mineral nanosystems and the biogenic magnetic nanosystems have to be as follows: the FMR signals of the synthetic materials must be anisotropic, the width of the signals has to be in the range of 60−100 mT, and the synthetic materials must demonstrate the anomalous dynamical effects described above.

Creation of synthetic organic-mineral nanomaterials that demonstrate the macroscopic quantum effects at the room temperature would open up new opportunities for solving different fundamental and applied problems by means of non-traditional approaches. In particular, the above materials could be employed when developing technical systems for storage and processing of information that use the principles of brain functioning.

4. Conclusions

Let us in summarise in brief the results reported in this work. The results of our studies show that the brain tissue should contain magnetic biominerals formed by iron oxides and hydroxides. These biominerals are formed by both physiological and pathological processes. Formation of the physiological biominerals is programmed on the level of genes, while the pathological biominerals are produced if the interaction of organic and mineral matters is disrupted, e.g., because of some changes in the properties of the organic matrix (broken chemical bonds, free radicals, surplus iron, etc.). As a result, an uncontrolled growth of inorganic mineral inclusions may take place.

The meaning of the magnetic biominerals is not restricted to the substances where the iron ions are accumulated. The results described in this article allow us to conclude that the physiological magnetic biominerals have an important part in functioning of the brain, and the pathogenic magnetic inclusions may cause brain diseases. Information about the magnetic biominerals localised in the brain tissue may stimulate further investigations of the problems related to the mechanisms of storage and processing of information in the brain tissue, and development of methods for preventing and treating brain diseases.

Following from our results, we conclude that the magnetic biominerals comprise a separate class of materials. Investigations of the hybrid organic-mineral biocomposites have a potential to result in discovery of new physical phenomena and finding solutions of many applied problems, using non-traditional approaches. The macroscopic quantum effects described above and detected at the room temperature represent a vivid illustration of specific properties of our objects. These unique effects demonstrate that the properties of biogenic nanocrystals are determined not only by their crystal lattice and symmetry, but also by the organic matrix.

Although the unique properties of the samples described here have been detected in strong microwave fields, one can assume that magnetic biominerals should also reveal some specific physical properties in their native state, i.e. in a living organism. On the basis of our results one can put forth an assumption about specific magneto-electric properties peculiar of the organic-mineral nanocomposites. This assumption agrees with the properties of MONA systems related to the presence of non-equilibrium electric charges in the nanoscale structural units of those systems. In other words, magneto-electric properties of the magnetic biominerals should be very important in the brain functioning and magneto-reception of birds or other living organisms.

For achieving further progress in this field, it is necessary to create synthetic analogues of the magnetic biominerals. When analysing the results obtained here, one can bring nearer the optimal technologies for creating these synthetic materials. The corresponding technologies must reproduce the environments typical for the living organisms, including formation of iron hydroxide nanoparticles associated with the organic matrix, and transformation of these hydroxides into iron oxides. The described dynamic effects may be used in order to control the properties of the synthetic materials. A presence of the macroscopic quantum effects at the room temperature must be the main criterion of compatibility in the properties of the synthesised materials and the magnetic biominerals of natural origin.

It is difficult to over-estimate the prospects associated with practical applications of synthetic materials possessing the macroscopic quantum effects at the room temperature. Among such prospects, one can recall creation of devices for information storage and processing using the principles of brain function. In particular, hybrid organic-mineral nanomaterials with the macroscopic quantum states existing at the room temperature may be used when solving a number of problems related to quantum computers.

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Анотація. *Описано аномальні властивості біогенних магнітних мінералів, локалізованих у тканинах мозку людини та тварин. Експерименти виконано за допомогою ферімагнітного резонансу. Показано, що в тканинах мозку можна зареєструвати сигнали ферімагнітного резонансу, обумовлені і фізіогенними, і патогенними біомінералами. Якщо мікрохвильова потужність перевищує критичне значення (~ 80 мВт), то фізіогенні магнітовпорядковані наночастинки виявляють унікальні динамічні ефекти. Ми вважаємо, що ці ефекти пов'язані з переходом біогенних магнітних наночастинок до макроскопічних квантових станів за кімнатної температури. Зроблено припущення, що фізіогенні магнітні біомінерали відіграють важливу роль у функціонуванні мозку, а патогенні біомінерали є причиною захворювань мозку. Описано основні принципи розробки технологій створення синтетичних матеріалів з макроскопічними квантовими ефектами за кімнатної температури. Проведено аналіз можливого використання одержаних результатів у вирішенні фундаментальних і прикладних проблем.*