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PROPERTIES OF NANOSCALE MAGNETICALLY ORDERED PARTICLES OF IRON OXIDES AND HYDROXIDES, SYNTHESIZED BY DIFFERENT TECHNOLOGIES

The characteristics of nanoscale magnetic-ordered particles, synthesized by different technologies, were determined by the methods of electron transmission microscopy, nuclear gamma resonance spectroscopy and magnetometry. The synthesis conditions in used technologies were close to the conditions that occur at magnetic biominerals formation in the living organisms. The factors that are most considerably affect the phase composition and magnetic characteristics of synthesized nanoparticles were determined. On the background of the obtained results, the possible means for creation of synthetic analogues of biogenic magnetic-ordered particles, localized in brain tissues, were analyzed.

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1. Introduction

It is well known that during last years the interest to nanomineralogy, nanophysics, nanotechnology and other nanosciences are rapidly grow. It happens due to the fact, that nanoscale particles have specific characteristics that are not inherent to the macroscopic particles [13, 14, 16, 20, 21]. Among the objects of nanomineralogy, the special interest is caused by the nanominerals of biogenic origin, which are formed as a result of vital activity of biological objects. It is known that physiogenic biominerals, which formation is programmed by the Nature at genetic level, are the nanominerals definitionally [16, 17]. This specified by the fact, that organic matrix can control the properties of mineral (inorganic) matter only in the case, when size of mineral particles are in the range of nanometers and, accordingly, when the contribution of surface energy to the total energy of particle is essential [16, 17].

Among the biominerals of different types the most interesting for us is biomagnetite which is formed in the organism of humans and other animals [6, 10, 12, 16, 17]. Many scientific works are describing the research of biomagnetite properties and its role in the functioning of biological objects. In particular, it is believed that birds and fish could orientate in the space by means of biomagnetite [12], and that biomagnetite plays an important role in the brain functioning [6, 16, 17]. It is necessary to solve at least two problems to clarify the mechanisms of biomagnetite functioning as a navigation device and as a system of information saving and processing in brain tissues. First of these problems is associated with the research of properties of nanomagnetite of biogenic origin, and second one — with creation of synthetic analogues of this biominerals.

It is shown in publications [3—7, 16, 17] that biomagnetite, that is localized in the brain tissues has a number of unique properties. In particular, room-temperature macroscopic quantum effects were registered for this object by means of magnetic resonance. It is necessary to note, that known at present time macroscopic quantum effects for other objects are registered only at extremely low (T = 4.2 K) or low (T = 77 K) temperatures. The research of properties of biomagnetite, that demonstrates the occurrence of room-temperature macroscopic quantum oscillations opens up new possibilities for creation of technical devices for information saving and processing, which would use principles of brain functioning, and also for the study of mechanisms of functioning and disease of this biological tissue [6, 7, 16, 17]. It is

important to underline that for the solving of the applied problems associated with biomagnetite, it is necessary to develop the technologies related to creation of synthetic analogues of this biogenic material. It is shown in the publications [16, 17] that magnetically ordered nanoparticles localized in brain tissues for which the term "biomagnetite" is used, actually are complex multiphase compound on the basis of different iron oxides and hydroxides.

Many different technologies for creation of magnetite nanoparticles are described in the literature, the review of such investigations one can find in the publications [11, 19]. At the same time, there are yet many unsolved problems in this area of knowledge. It is concerned, in particular, both synthesis technologies and research of the properties of nanoparticles that have been obtained by different technologies. The problems concerned with the creation of multiphase magnetic particles that could be considered as synthetic analogues of biomagnetite remain unexplored.

The goals of this work were to investigate the phase composition, size and the magnetic characteristics of magnetically ordered nanoparticles, synthesized by different technologies, and to use the obtained information for the analysis of feasible technologies for creation of synthetic analogues of biogenic magnetic nanoparticles localized in the brain tissues.

2. Studied samples and synthesis technologies

One can assume that the most optimal technologies for synthetic analogues of biomagnetite creation are the technologies with the conditions of nanoparticles formation, which are maximally close to the conditions that are realized during formation of biomagnetite in the living organism. The conditions of the magnetite formation, for example, in bacteria [1], are the following: aqueous medium in which iron (III) oxyhydroxide initially appears in membrane vesicle, after that, one-third of iron (III) ions are reduce to iron (II) by means of intracellular reducing agents (for example, ascorbic acid). It is believed that magnetite is formed by further dehydration of created substance. Thus, it was shown that the oxygen concentration is strongly affecting the process of magnetite biomineralization, namely: the maximal yield of magnetite occurs at the concentrations of oxygen about 1 %. Meanwhile, membrane vesicle, that acts part of restrictor, controls a size and morphology of magnetite particles and also stabilizes the surface of nanoparticles. Notably, the basic conditions for the biogenic magnetic nanoparticles creation are following: aqueous medium, minimal oxygen concentration, stabilization of particles' surface. Technologies of synthetic magnetic nanoparticles creation, developed in this work, are sufficient for the above-listed conditions.

The following materials were used for the synthesis of nanoparticles: distilled water, concentrated hydrochloric acid HCl, solution of ammonia in water NH_4OH (all — "Chimlaborreactiv"), iron (II) sulfate heptahydrate $FeSO_4 \cdot 7H_2O$, iron (II) sulfate tetrahydrate $FeSO_4 \cdot 4H_2O$, iron (III) chloride hexahydrate $FeCl_3 \cdot 6H_2O$, dextran, chitosan, 25 % glutaraldehyde solution $OHC(CH_2)_3CHO$, glacial acetic acid CH_3CO_2H, potassium nitrate KNO_3, potassium hydroxide KOH, epichlorhydrin, sodium tetrahydridoborate $NaBH_4$ (all — Sigma-Aldrich), tetraethoxysilane (TEOS) $SiO_4(C_2H_5)_4$, Fluka, ethanol rectifying. All solutions were prepared using distilled water.

In this work the main attention was paid to four samples that were synthesized by different technologies. The first three samples were synthesized by the method of hydrothermal precipitation of iron (II) salt in aqueous medium in the presence of weak oxidant. All manipulations were performed in the nitrogen atmosphere. The reagent solutions (1400 ml of the distilled water, 200 ml of 2.5 M KOH solution, 200 ml of 1 M KNO_3 solution, 200 ml of 1 M $FeSO_4 \cdot 7H_2O$ solution) were mixed quickly in the reaction vessel, the temperature of the reaction mixture was raised up to 90 °C. Time of reaction is 2 hours after the necessary temperature adjustment. After the reaction completing, the created nanoparticles of magnetite were rinsed by an alkali (0.05 M KOH) using the magnetic separation method. Immediately after obtaining of magnetic nanoparticles the 100 ml of 10 % dextran solution in 1 M KOH were added to the nanoparticles' suspension. After 2 hours of these solutions incubation, 100 mg of $NaBH_4$ were added to the mixture, the mixture temperature was raised up to 50 °C and the incubation under this temperature was continued during 2 hours. After that, 2.5 ml of epichlorhydrin were added dropwise and the mixture was incubated for more 10 hours at the temperature of 50 °C. Thus, magnetic nanoparticles covered by dextran were obtained (sample 1).

Samples 2 and 3 were obtained as follows. All manipulations were performed in the nitrogen atmosphere. The reagent solutions (1400 ml of the distilled water, 200 ml of 1.5 M KOH solution,

200 ml of 2 M KNO_3 solution, 200 ml of 1 M $FeSO_4 \cdot 7H_2O$ solution) were mixed quickly in the reaction vessel, the temperature of the reaction mixture was raised up to 90 °C. Time of reaction is 2 hours after the necessary temperature adjustment. After termination of the reaction, the created nanoparticles of magnetite were washed by an alkali (0.05 M KOH) using the magnetic separation method. Immediately after obtaining of magnetic nanoparticles the 100 ml of 2 % γ-aminopropyltriethoxysilane solution in 0.05 M KOH were added to the nanoparticles' suspension, the reaction vessel was inserted into the thermostat and incubated at 90 °C during 2.5 hours at weak ultrasonic treatment. The reaction vessel was leaved in the thermostat overnight. After the reaction completing, the created nanoparticles of magnetite were rinsed by distilled water using the magnetic separation method. Thus, the sample 2 was obtained.

After that, the part of obtained magnetite nanoparticles was mixed with distilled water in order to obtain suspension for the next sample synthesis. For this purpose 14 ml of 0.4 M $NaIO_4$ solution were added to 100 ml of 10 % hydroxyethylstarch solution in water. Mixture was mixed during 2 hours at a room temperature. The obtained mixture of the modified starch was added to 100 ml of solution of modified by γ-aminopropyltriethoxysilane magnetic nanoparticles; a suspension was treated ultrasonically and incubated during 4 hours at a temperature 60 °C. After the reaction completing, the created nanoparticles of magnetite were rinsed by distilled water using the magnetic separation method. Thus, the sample 3 was obtained.

A fourth sample was synthesized by the method of co-precipitation of Fe^{2+} and Fe^{3+} with ammonia in aqueous medium at normal conditions. Stock solutions of 1 M $FeCl_3 \cdot 6H_2O$ and 2 M $FeSO_4 \cdot 4H_2O$ were prepared as a source of iron by dissolving the respective chemicals in 2 M hydrochloric acid under stirring. Stock solution of 1 M NH_4OH was prepared by dilution of concentrated NH_4OH solution. The reagents solutions (4 ml of 1 M $FeCl_3 \cdot 6H_2O$ solution and 1 ml of a 2 M $FeSO_4 \cdot 4H_2O$ solution) were mixed quickly in reaction vessel, and 50 ml of ammonium solution was added drop-by-drop to reaction mixture under slow mechanical stirring. After the reaction completing, magnetic particles were lightly dispersed using ultrasound dispergator, rinsed three times with distilled water to remove the residual surfactant and unreacted reagents. 25 ml of distilled water were added to the obtained magnetic nanoparticles. After that, 0.1 g of chitosan in 1 % acetic acid and 8,25 g of urea were added to the reaction mixture and this mixture was incubated during 2 hours at 95 °C. After mixture cooling, the obtained magnetic nanoparticles were rinsed three times with distilled water to remove the residual surfactant and unreacted reagents. Thus, the sample 4 was obtained.

3. Methods of experimental investigations of the synthesized nanoparticles

The size and morphology of magnetic nanoparticles were observed by the method of transmission electron microscopy (TEM) using PEM-U (Sumy, Ukraine). At investigation using transmission electronic microscopy method, the samples on the thin film are examined with an accelerated electron beam with the energy of 75 keV. During preparation of the samples for transmission electron microscopy the special facilities were used, that allow to avoid aggregation of nanoparticles. This is very important, because aggregation of nanoparticles prevents to obtain the information about the size of nanoparticles and their size distribution.

The crystal-chemical properties of the state of iron cations in the structure of magnetite and coexisting iron-containing phases, their valency, coordination and distribution on non-equivalent positions, and also the internal magnetic fields on their nuclei were studied by the method of nuclear gamma-resonance spectroscopy (NGR-spectroscopy). NGR-spectra were obtained on the "Wissel" spectrometer (FRG); the source of the emission was ^{57}Co in the matrix of Cr. The spectra processing was carried out with the use of the program which realizes a least-squares method.

Magnetic researches were performed by means of magnetometer with Hall sensor (Kyiv, Ukraine), that is intended for the measuring of hysteresis loop parameters of powder-like isotropic and anisotropic materials by maximum and partial hysteresis cycles. In this device, the measurement of parameters of magnetization curves and hysteresis loops are taking place in the open magnetic circuit. Cylinder-shaped observable sample is introduced to the interpolar space of electromagnet. The differential pair of Hall sensors with the magnetic axes oriented parallel to the vector of electromagnet external magnetic field is located in immediate proximity to the sample. The measuring sensors with such orientation don't respond to the external

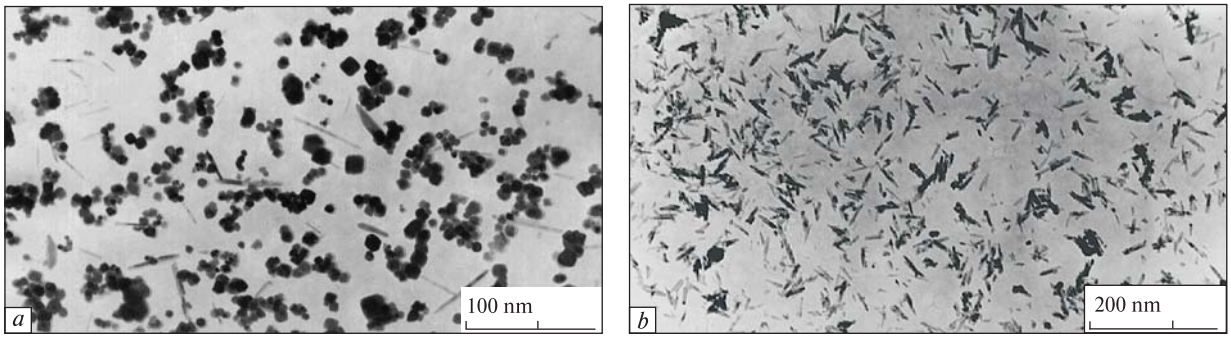

Fig. 1. Electron of micrographs of synthesized nanoparticles: *a* — sample 1; *b* — sample 4.

field, and the origin of measured signal is related only to the sample field component, that is in direct proportion to value of its magnetic moment. The calibration with the use of standard specimen with known saturation magnetization was carrying out for determination of absolute value of magnetic moment (magnetization) of observable samples. The nickel was used as a standard specimen, the saturation magnetization of which is determined with high accuracy (54.4 $A \cdot m^2/kg$ at a room temperature).

4. Experimental results and discussion

4.1. ***Transmission electron microscopy***. Electron micrographs of synthesized nanoparticles obtained by the method of hydrothermal precipitation of iron (II) salt in aqueous medium in the presence of weak oxidant (*a* — sample 1) and by the method of co-precipitation (*b* — sample 4) are shown on the Fig. 1. The presented microphotographs are show that magnetic nanoparticles obtained by the method of hydrothermal precipitation of iron (II) salt in aqueous medium in the presence of weak oxidant have cubic shape and the mean size of the magnetite core is 30 nm. Magnetic nanoparticles, obtained by the co-precipitation method are elongated and the mean size of the magnetite core of these particles is approximately 100 nm (the mean sizes of magnetite cores of all synthesized nanoparticles are shown in the Table 1). Thus, on the basis of the obtained results one can conclude, that synthesis of nanoparticles by the method of the hydrothermal precipitation, that is conducted in the oxygen-free atmosphere and at the increased temperature, allows to obtain the cubic-shaped nanoparticles of less size, and synthesis of nanoparticles by the method of co-precipitation, that conducted in oxygen atmosphere and at room temperature results in formation of elongated particles of greater size.

Table 1. **Descriptions of the synthesized magnetic nanoparticles**

Sample	Coverage	Particles size, nm	Saturation magnetization, $A \cdot m^2/kg$	M_r / M_s
1	Dextran	30	83	0
2	γ-APS	25	—	—
3	Hydroxyethylstarch	25	73	0
4	Chitosan	100	30	0.17

4.2. ***Nuclear gamma-resonance (NGR) spectroscopy***. The NGR-spectra of investigated samples are shown at the Fig. 2, the parameters of these spectra are shown in the Table 2. Spectrum of sample 1 is presented by two sextets of magnetic splitting (Fig. 2, *a*). On the basis of comparison of sextets parameters with literature data [2, 15], the spectrum of sample 1 was related to resonance absorption in magnetite. Thus, the sextet with the greater value of H_{eff} was related to resonance contribution of Fe^{3+} ions in tetrahedral (*A*) positions of magnetite structure, and the sextet with smaller H_{eff} was related to total contribution of Fe^{3+} and Fe^{2+} ions in octahedral (*B*) positions. Inseparability of Fe^{3+} and Fe^{2+} contributions in octahedral sub-lattice is explained by an electronic exchange between them. On the assumption of structural data about quantitative correlation of positions *A* and *B* in the unit cell of magnetite (8 : 16), the ratio of lines areas of series *A* and *B* (S_A / S_B) for magnetite of stoichiometrical composition is 0.5. Deviation of S_A / S_B ratio from this value is related with occurrence of isomorphic substitutions in a structure, with oxidization of Fe^{2+} or with the presence of non-identified admixture phases with the parameters, that are close to the sextets *A* and *B*. Experimentally found value S_A / S_B for a sample 1 is 0.859 that is the evidence of considerable oxidization of octahedral Fe^{2+} cations.

Spectra of samples 2 and 3 (Fig. 2, *b*, *c*) are presented by superposition of three sextets of

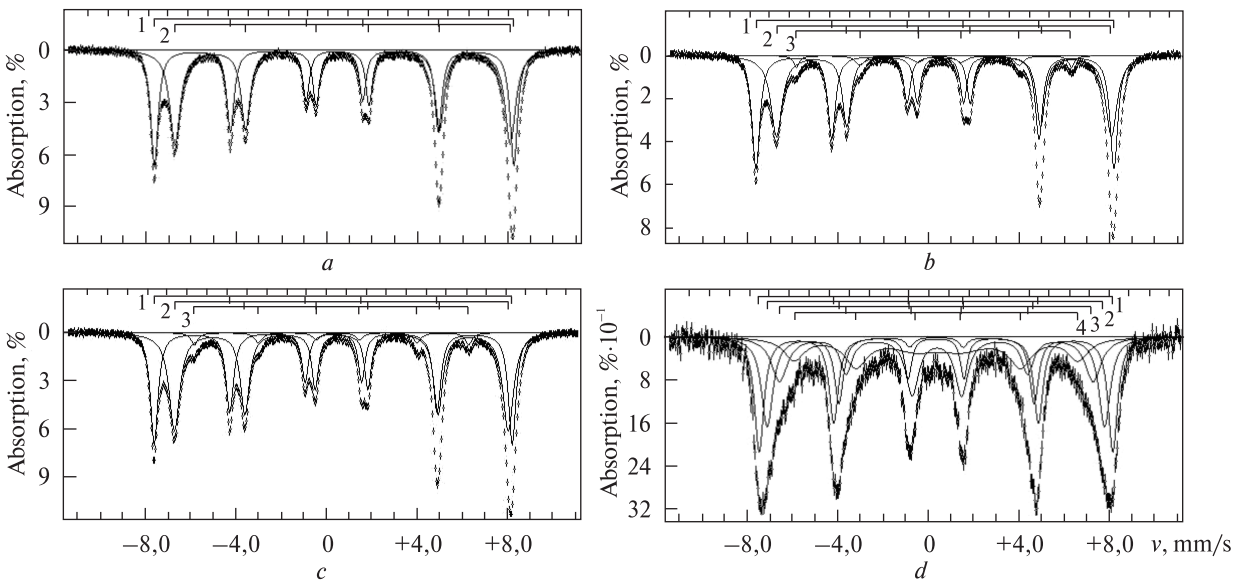

Fig. 2. NGR-spectra of synthesized samples: *a—d* — samples 1—4 correspondingly.

magnetic splitting, two of which, with the greater values of the magnetic splitting, were referred to magnetite by the parameters values. The value of ratio S_A / S_B in a spectrum of the sample 2 is 0.992 that is the evidence of increasing of iron oxidation degree in its structure in comparison with sample 1.

Table 2. **Parameters of NGR-spectra of the synthesized samples**

Sample	Iron position	H_{eff}, kOe	I. S.	Q. S.	G	S, %	(S_A/S_B)
			mm/s				
1	*Magnetite*						
	A-position	491	0.29	0.01	0.35—0.39	46.2	0.859
	B-position	458	0.65	0.00	0.35—0.57	53.8	
2	*Magnetite*						
	A-position	490	0.29	0.02	0.36—0.41	46.9	0.992
	B-position	459	0.67	0.01	0.35—0.61	47.3	
	Goethite						
		376	0.35	0.25	0.31—0.57	5.8	—
3	*Magnetite*						
	A-position	490	0.29	0.01	0.35—0.41	42.6	0.816
	B-position	457	0.65	0.01	0.37—0.58	52.2	
	Goethite						
		376	0.35	0.27	0.37—0.42	5.2	—
4	*Maghemite*						
	1	483	0.32	0.00	0.39—0.50	29.5	—
	2	460	0.33	0.03	0.45—0.62	23.3	
	3	428	0.35	0.03	0.63—0.86	25.8	
	Goethite						
	1	388	0.37	0.10	1.11—2.45	24.1	—

N o t e. H_{eff} — effective magnetic field on the iron nucleus; I.S. — an isomer shift relative to the α-iron; Q.S. — quadrupole splitting; G — absorption line half-width; S — relative area of the component. *Measurement error*: H_{eff} — ±5 kOe, I. S., Q. S., G — ±0.03 mm/s, S — ±5 %.

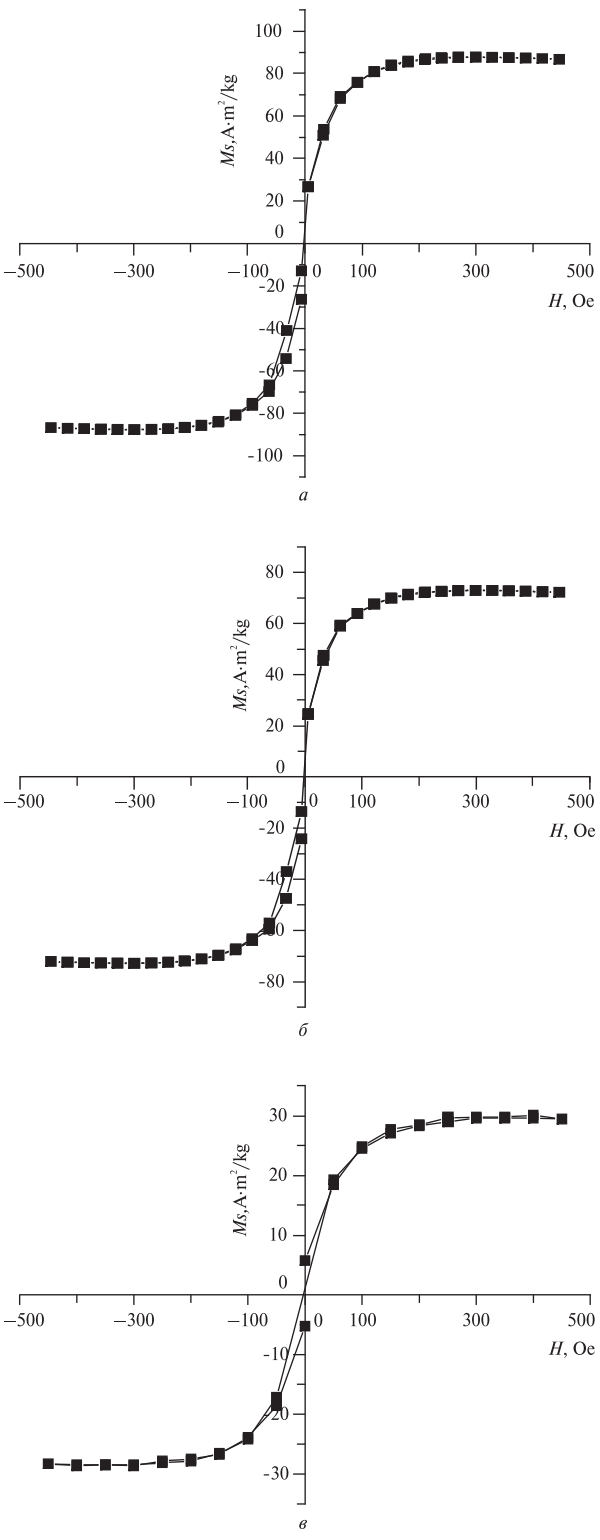

Fig. 3. Magnetization curves for the samples 1 (*a*), 3 (*b*), 4 (*c*).

Third sextet with the minimum value of splitting was related to goethite (α-FeOOH) according to the comparison of its parameters with literature data [18]. The resonance contributions of goethite to the spectra of samples 2 and 3 are 5.8 % and 5.2 %, correspondingly. The oxidation degree of structural iron in magnetite of the sample 3 is minimum ($S_A / S_B = 0.816$) in comparison with two mentioned above samples.

NGR-spectrum of sample 4 is characterized by significant decrease of resonance absorption and broadening of the spectra lines. The last is the evidence of complex superposition of several resonance sextets in the aggregate spectrum. Spectrum of sample 4 was approximated by four sextets of the magnetic splitting (Fig. 2, *d*). Three sextets with the high values of H_{eff} (483, 460 and 428 kOe) and total contribution of 78.6 % were referred to the resonance absorption of gamma-quants by the nuclei of Fe^{3+} ions in the structure of maghemite (γ-Fe_2O_3) [18] according to the spectroscopic parameters. The sextet with the minimum value of H_{eff} (388 kOe), with maximal value of the quadrupole splitting and total contribution of 21.4 % was referred to the resonance absorption of Fe^{3+} in the goethite structure. The presence in the spectrum of three components of maghemite could be related with the characteristic properties of the structure of surface layers of nanodispersed particles and their inhomogeneity.

Considerable broadening of resonance lines of goethite one could explain by the watering of its' structure and formation of hydrogoethite which meets the formula α-FeOOH · nH_2O, where *n* could be in a range from 0 to 0.5. In is necessary to note, that hydrogoethite have antiferromagnetic and weak ferrimagnetic properties. Water and the products of its dehydration could affect the weak ferrimagnetic properties only in the case of formation non-homogeneities in the crystal lattice that are disturbing the collinearity of Fe^{3+} spins. The water in the structure of goethite and structure defects of both iron-containing phases, probably, causes the decreasing of resonance absorption in the spectrum of sample 4.

On the background of the obtained results it is possible to conclude, that synthesis of nanoparticles by the method of the hydrothermal precipitation, that is conducted in the oxygen-free atmosphere allows to obtain magnetite nanoparticles with the small admixtures of goethite (that is formed due to the oxidization of magnetite by oxygen, that was not completely removed from the reaction mixture), and synthesis by the method of co-precipitation, that was conducted in the oxygen atmosphere and at a room temperature resulted in

formation of maghemite particles with the admixtures of goethite.

4.3. ***Magnetic properties***. Magnetic characteristics were experimentally investigated for the samples 1, 3 and 4. Obtained results are shown at the Fig. 3, where the hysteresis curves are figured for the observable samples, and also in the Table 1. It is known, that hysteresis curves are characterized by saturation magnetization (M_s), saturation remanence (M_r) and coercivity (H_c). Analysis of these values, and also the M_r/M_s ratio enables one to make a conclusion about the peculiarities of the magnetic state of observable samples. It is known, that magnetic characteristics of magnetite are determined by its structure. Magnetite has ferrimagnetic properties, as magnetic moments of octahedrically coordinated ions Fe^{2+} and Fe^{3+} are parallel to each other and antiparallel to the magnetic moment of Fe^{3+} ions, that located in the vertexes of tetrahedrons. The hysteresis curves of magnetite nanoparticles are essentially depend on the domain state of these particles [8, 9, 12]. The individual magnetic particles could be subdivided into superparamagnetic, single domain, pseudo-single domain (the presence of coupled single domain states) and multidomain states. By means of the experimentally registered hysteresis curves and its characteristics it is possible to make conclusions about the magnetic state of nanoparticles [9].

From the experimental dependencies, presented on the Fig. 3, it is possible to see that the saturation magnetization could be determined accurately for observable samples and these values are unequal for different samples (Table 1). The different values of saturation magnetization for samples 1 and 3 are conditioned, probably, by the different degree of these samples' imperfection and by the presence in the sample 3 of goethite phase. The essential decrease of the M_s value for a sample 4 is conditioned, probably, mainly by the fact, that the structure of this sample is represented by the maghemite with the high degree of crystal lattice disordering, and also by the presence of goethite phase in this sample. The M_r value could reliably be determined only for a sample 4 (Table 1). The M_r value for a sample 1 is equal to zero, and this value for a sample 3 is very small, that obstructs its measuring. Coercivity H_c for samples 1 and 3 are equal to zero. This value for the sample 4 is not equal to zero, but is very small, that obstructs the experimental determination of its value.

The determination of M_r/M_s ratio is an important test in the differentiation between single- and multidomain particles. In our case, the shapes of the hysteresis curves of samples 1 and 3 are extremely thin, i. e. $M_r/M_s \approx 0$ that is the characteristic property of superparamagnetic nanoparticles. Superparamagnetic nanoparticles demonstrating very rapid initial increasing of magnetization with the field increasing, then the gradual increasing of magnetization up to saturation is take place. In addition, superparamagnetic particles do not reveal the saturation remanence and coercivity. These characters are present for the hysteresis curves, registered for samples 1 and 3.

The ratio M_r/M_s for sample 4 is approximately 0.17. According to the publication [9], the hysteresis curves for pseudo-single domain particles are characterized by the M_r/M_s values in a range of 0.1—0.5. That is why, it is possible to assume, that nanoparticles of sample 4 are pseudo-single domain. This conclusion is confirmed by the data about the size of sample 4 particles, that was obtained by the method of electron microscopy (100 nm), and also by the data about the composition and structure of these particles, determined by NGR-spectroscopy.

Thus, on the basis of M_r/M_s ratio values, size of magnetic nanoparticles and their phase composition one could make a conclusion about the domain state of the synthesized magnetic nanoparticles. The particles of samples 1 and 3, that were synthesized by the hydrothermal precipitation of iron (II) salt in aqueous medium in the presence of weak oxidant, that have sizes of 25—30 nm and that consist mainly of magnetite are superparamagnetic. Particles of sample 4 that synthesized by the method of co-precipitation, that have sizes of 100 nm and that consist of maghemite and goethite mixture are pseudo-single domain.

5. Conclusion

The obtained experimental results are allowing to analyze the influence of synthesis conditions on the size, phase composition and magnetic properties of synthesized nanoparticles, obtained by different technologies. Comparison of the described above characteristics of synthesized particles with respective characteristics of biogenic magnetic nanoparticles can be the basis for the solving of the problem, associated with development of creation technologies of synthetic analogues of magnetic-ordered particles, localized in the brain tissues. For the decision of these problems, the processes of nanoparticles' formation, which are described above in this work, must be held in the

presence of organic matrix, that is jointly with magnetic-ordered nanoparticles need to form the hybrid organic-mineral nanosystem. The above mentioned information about the dependence of phase composition and magnetic characteristics of nanoparticles from the peculiarities of synthesis technologies could be used to choose the optimal conditions of creation of the synthetic analogues of biominerals. On the background of described above properties of synthetic nanoparticles as well as the properties of biogenic magnetic biominerals, it is possible to assume, that optimal technologies of creation of considered synthetic organic-mineral materials must include the formation of iron hydroxide nanoparticles associated with organic matrix, and then, the transformation of these hydroxides into iron oxides. Such transformation could be held due to the processes of dehydration and dexydroxylation, as well as due to the additional oxidation or reduction of iron ions. The criterion of equivalence of the synthetic hybrid organic-mineral nanosystems to the biogenic magnetic nanosystems localized in brain tissues must be the presence at synthetic materials of the above mentioned coherent effects that are demonstrated by the magnetic nanoparticles of biogenic origin. In conclusion, the following should be mentioned, the creation of synthetic organic-mineral nanomaterials, that demonstrating the unique characteristics of biogenic magnetite, opens up the new possibilities for many fundamental and applied problems' solving.

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РЕЗЮМЕ. За допомогою методів електронної трансмісійної мікроскопії, ядерної гама-резонансної спектроскопії та магнітометрії визначені характеристики нанорозмірних магнітовпорядкованих частинок, синтезованих за різними технологіями. У використаних технологіях умови синтезу наближалися до тих умов, які спостерігаються під час формування магнітних біомінералів у живих організмах. Було визначено фактори, що найбільш суттєво впливають на фазовий склад та магнітні характеристики синтезованих наночастинок. На підставі отриманих результатів проаналізовані можливі шляхи створення синтетичних аналогів біогенних магнітовпорядкованих частинок, локалізованих в тканинах мозку.

РЕЗЮМЕ. С помощью методов электронной просвечивающей микроскопии, ядерной гамма-резонансной спектроскопии и магнитометрии определены характеристики наноразмерных магнитоупорядоченных частиц, синтезированных по разным технологиям. В использованных технологиях условия синтеза приближались к тем условиям, которые имеют место при формировании магнитных биоминералов в живых организмах. Определены факторы, которые наиболее существенно влияют на фазовый состав и магнитные характеристики синтезированных наночастиц. На основании полученных результатов проанализированы возможные пути создания синтеических аналогов биогенных магнитоупорядоченных частиц, локализованных в тканях мозга.