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RESEARCH ARTICLE

Emergent properties of magnetic ions and nanoparticles in micellar solutions of surfactants: Use in fine technologies¹

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Abstract

Objectives. To establish expected emergent (unexpected) properties of magnetic materials when obtained in aqueous micellar solutions of surfactants (aqueous quantum materials), and their use in fine technologies.

Methods. Chemical synthesis of magnetic nanoparticles in aqueous micellar solutions of surfactants of various nature. Characterization of magnetic solutions and nanoparticles by magnetic measurements, spectroscopy, diffractometry, small-angle X-ray diffraction, scanning probe microscopy, and others.

Results. The term “water quantum material” refers to materials (micellar solutions) whose properties are mainly determined by the nuclear quantum effect on macroscopic scales (emergent property). Micellar solutions exhibit phenomena and functionality not always consistent with the classical theory of micellization. The article presents in detail the experimental results that suggest the manifestation of the emergent properties of magnetic materials obtained in aqueous micellar solutions of surfactants. In particular, Gd³⁺ ions in an aqueous micellar solution of sodium dodecyl sulfate exhibit paramagnetic properties, possibly indicating their random arrangement in solution contrary to the classical theory of micellization with an ordered adsorption layer on micelles. Hybrid Pt–Gd nanoparticles are formed in a quantum material

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with cetylpyridinium chloride as a matrix, although Gd^{3+} ions must be repelled by CP^+ ions on micelles. Nanosized powders of cobalt ferrite and nickel ferrite obtained in a micellar solution of sodium dodecyl sulfate have superparamagnetic properties, although the presence of their precursor ions in the adsorption layer in classical micelles should lead to ferromagnetic properties. **Conclusions.** The synthesis of nanoparticles in a quantum material opens up the possibility of reducing ions of different signs in one stage during the processing of metallurgy waste, in order to obtain nanoparticles of various metals and their composites. Magnetic nanoparticles obtained in a quantum surfactant material self-assemble on various substrates, enabling the creation of materials whose residual magnetization and coercive field can be controlled at room temperatures.

Keywords: magnetic nanoparticles, nuclear quantum effects, water quantum materials, emergent properties, metallurgy waste processing

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НАУЧНАЯ СТАТЬЯ

Эмерджентные свойства магнитных ионов и наночастиц в мицеллярных растворах ПАВ: Использование для тонких технологий

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Аннотация

Цели. Выявить предполагаемые эмерджентные (неожиданные) свойства магнитных материалов при их получении в водных мицеллярных растворах поверхностно-активных веществ (ПАВ) (водных квантовых материалах), которые можно использовать для тонких технологий.

Методы. Химический синтез магнитных наночастиц в водных мицеллярных растворах ПАВ различной природы; характеристика магнитных растворов и наночастиц методами магнитных измерений, спектроскопии, дифрактометрии, малоугловой рентгеновской дифракции, сканирующей зондовой микроскопии и другими.

Результаты. Термин «водный квантовый материал» относится к материалам (мицеллярным растворам), свойства которых в основном определяются ядерным квантовым эффектом в макроскопических масштабах (эмерджентное свойство). Мицеллярные растворы демонстрируют явления и функциональные возможности, не всегда соотносимые с классической теорией мицеллообразования. В статье подробно представлены экспериментальные результаты, которые позволяют предположить проявление

эмерджентных свойств магнитных материалов, получаемых в водных мицеллярных растворах ПАВ. В частности, ионы гадолиния Gd^{3+} в водно-мицеллярном растворе додецилсульфата натрия проявляют парамагнитные свойства, что, возможно, указывает на их беспорядочное расположение в растворе вопреки классической теории мицеллообразования с адсорбционным упорядоченным слоем на мицеллах. Гибридные наночастицы $Gd-Pt$ образуются в квантовом материале с хлоридом цетилпиридиния в качестве матрицы, хотя ионы Gd^{3+} должны отталкиваться ионами цетилпиридиния ЦП⁺ на мицеллах. Наноразмерные порошки феррита кобальта и феррита никеля, получаемые в мицеллярном растворе додецилсульфата натрия, обладают суперпарамагнитными свойствами, хотя присутствие их прекурсорных ионов в адсорбционном слое в классических мицеллах должно было бы привести к ферромагнитным свойствам.

Выводы. Синтез наночастиц в квантовом материале открывает возможность восстановления ионов разных знаков за одну стадию при переработке отходов металлургии с целью получения наночастиц различных металлов и их композитов. Магнитные наночастицы, получаемые в квантовом материале ПАВ, самоорганизуются на различных подложках, что позволяет создавать материалы, остаточная намагниченность и коэрцитивное поле которых можно регулировать при комнатных температурах. Таким образом, показано, каким образом эмерджентные свойства квантовых материалов можно применять для тонких технологий.

Ключевые слова: магнитные наночастицы, ядерный квантовый эффект, водные квантовые материалы, эмерджентные свойства, переработка отходов металлургии

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INTRODUCTION

Ionic surfactants are often used to obtain magnetic nanoparticles. They play the role of matrices for the localization of d-block element ions [1–4]. According to classical theory, direct surfactant micelles in water have the structure of a hydrocarbon core with a double electric layer of ions [5]. The electrical double layer consists of an adsorption and a diffuse layer. The ions of the adsorption layer are densely packed and organized. The degree of ionization of micelles and the energy of Gibbs micelle formation can thus be established. The ions of the diffuse layer, on the contrary, are washed out by thermal energy. Based on such an organization of magnetic ions in the adsorption layer, a strong exchange interaction between them can be expected

with the manifestation of ferromagnetic properties. However, this is not observed [6]. Another emergent property is associated with the synthesis of metal nanoparticles from positive ions in micelles of cetylpyridinium chloride $C_{16}H_{33}C_5H_5NCl$ [7–9]. Gadolinium ions Gd^{3+} should not penetrate into the hydrocarbon core of a classical micelle, since they are repelled by the positive $C_{16}H_{33}C_5H_5N^+$ ions of the micelle. Therefore, the matrix or protective properties of micelles should not appear. However, these properties are used very successfully.

For more purposeful application, these and other contradictions or emergent properties require a more detailed study. This is especially important for *in vivo* use, where synergism and antagonism of drugs or magnetic probes with the quantum properties of a biological cell is possible [10–12].

We previously conducted similar studies with the same goal, but the mystery of the nature of this phenomenon did not allow us to explain the contradictions we observed. The time has come now to return to the causes of the magnetic properties of ions and nanoparticles obtained in the matrices of quantum materials.

Let us briefly dwell on the probable mechanism of this phenomenon. Solid quantum materials operate at low temperatures where quantum fluctuations are more pronounced. Solid quantum materials reveal completely new phenomena and functions in the Mott transition, high-temperature superconductivity, topological superconductivity, colossal magnetoresistance, and giant magnetoelectric effect [13].

The quantum properties of water have been the focus of intensive study, in order to understand the role of quantum phenomena in the properties of water. However, these studies are based on calculations of various water models and depend on the choice of parameters proposed by the researchers themselves. Therefore, the results are very inconsistent. Water does not have the properties of a quantum material. The quantum fluctuations in it need to be “woken up”.

The unravelling of the mystery of quantum phenomena in aqueous solutions was made possible by the fact that for the first time the presence of accompanying phenomena was shown. This consisted namely of an extended phase transition in an ensemble of small aqueous systems and micellization [14–17]. The micelle formation process and the accompanying liquid-liquid phase transition are two sides of the same coin. Strong fluctuations of the extensive properties of water (thermal fluctuations) appear in the area of formation of spherical micelles, due to the smallness of the ensemble of water (6–14 molecules), corresponding to the size of surfactant molecules. They, in turn, stimulate the manifestation of quantum fluctuations of water molecules and charges. Organized chaos or correlation of thermal and quantum fluctuations arises. Quantum fluctuations at a size of 0.2–0.3 nm with the duration of a picosecond form thermal fluctuations (cavities) for micelles with the capture of water molecules at a size of 4–6 nm with diffusion coefficients of the order of $4 \cdot 10^{-6} \text{ cm} \cdot \text{s}^{-1}$ [17].

Magnetic ions and nanoparticles in micellar aqueous solutions are assumed to be present inside a quantum micelle or an organized chaos of water and surfactants. When attempting to measure electrical conductivity or electromotive force, the electromagnetic field of the device destroys quantum fluctuations and the micelle shows classical behavior. The reducing agent hydrazine hydrate does not affect the nuclear quantum effect. Such a theoretical explanation of the manifestation of

emergent properties is still debatable. Nevertheless, these properties can already be used for practical purposes.

In this article, as part of the discussion, we consider only the supposed emergent properties of magnetic materials when they are obtained in micellar surfactant solutions. The first part of the article discusses the magnetic properties of ions, then we will consider the features of self-organization and behavior of magnetic nanoparticles. In conclusion, we will show how a micellar surfactant solution can be used in a hybrid waste processing technology to obtain metal nanoparticles, metal oxides, and to create self-assemblies of magnetic nanoparticles.

MATERIALS AND METHODS

The main reagents used were cetylpyridinium chloride $\text{C}_{16}\text{H}_{33}\text{C}_5\text{H}_5\text{NCl}$ (CPC) (99%, *Sigma-Aldrich*, USA), sodium dodecyl sulfate (SDS) (99%, *Shostka Chemical Plant*, Russia), gadolinium acetate $\text{Gd}(\text{CH}_3\text{COO})_3 \cdot 3\text{H}_2\text{O}$ (chemically pure, *Vekton*, Russia), platinum hydrochloric acid $\text{H}_2[\text{PtCl}_6] \cdot 6\text{H}_2\text{O}$ (99%, *SilverSalt*, Russia), hydrazine hydrate $\text{N}_2\text{H}_4 \cdot \text{H}_2\text{O}$ (100%, *Clearysynth*, India), $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ (chemically pure, *Russian Vitriol Company*, Russia), $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ (chemically pure, *Fairsky Industrial Co.*, China) and $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$ (chemically pure, *Fairsky Industrial Co.*, China) were used to obtain CoFe_2O_4 and NiFe_2O_4 nanoparticles. A mixture of toluene and isoamyl alcohol in a volume ratio of 4:1 (purified grade reagents from *Fluka*, Switzerland) was used as the organic phase in the process of flotation extraction.

For the synthesis of nanoparticles, an ultrasonic disperser UZDN-2 (*Techcenter*, Russia) was used. The diffraction patterns of the nanopowders were recorded on a DRON 3M X-ray diffractometer (*Burevestnik*, Russia) with a copper emitter. The size and shape of nanoparticles were determined using a JEOL JEM-1011 transmission electron microscope (TEM) (*JEOL*, Japan) at an accelerating voltage of 100 kV. The content of platinum in the Pt–Gd nanopowder was determined using a Kvant-Z atomic absorption spectrometer (*Kortek*, Russia) with an electrothermal atomizer (graphite furnace). Magnetic studies were carried out on magnetic balances by the ponderomotive method, as well as on the universal “Cryogenic high field measurement system” (CFMS, *Cryogenic*, United Kingdom). In addition to the usual measurements of the magnetic moment as a function of the magnetic field and temperature, we used the technique of measuring the magnetic susceptibility after cooling in zero (zero field cooling, ZFC) and low (field cooling, FC) magnetic

fields. The characteristic maximum on the ZFC branch at the blocking temperature was used to estimate the sizes, as well as the size distribution of nanoparticles. Topographic and elemental analyzes were performed on a Philips SEMS 515 scanning electron microscope (*Philips*, Netherlands) with an EDAX ECON IV microanalyzer. The photographs of the obtained powder particles were taken with an Olympus GX71 metallographic microscope (*Olympus*, Japan).

RESULTS AND DISCUSSION

Magnetic properties of Gd^{3+} obtained in a quantum material with sodium dodecylsulfate (SDS)

We tested the magnetic ordering of Gd^{3+} ions by adding gadolinium acetate $(CH_3COO^-)_3Gd^{3+}$ (GA) to SDS in the ratio (1:1, mol) [6]. Solutions of 0.05 M GA at 298 K had a magnetic susceptibility equal to $1.8 \cdot 10^{-7} \text{ m}^3 \cdot \text{kg}^{-1}$, i.e., they were diamagnetic. When GA was added to a solution of SDS (1:1), no precipitation was observed. The micellar solution of gadolinium dodecyl sulfate obtained in this way became paramagnetic with a magnetic susceptibility equal to $2.0 \cdot 10^{-7} \text{ m}^3 \cdot \text{kg}^{-1}$ (Table). If we assume that gadolinium dodecyl sulfate at such a concentration is soluble in an aqueous solution of GA, then without the action of a magnetic field, the Gd^{3+} ions, and, consequently, Na^+ ions in solutions with spherical micelles, are completely randomly oriented. They do not have the structure of the adsorption layer of a classical micelle. The paramagnetic properties of such solutions are preserved in the temperature range of 275–315 K.

On the other hand, if the Gd^{3+} ions are built into an order characteristic of a lamellar micelle (liquid crystal) (Fig. 1), as in the GA–water–undecane system, the Gd^{3+} ion has ferromagnetic properties.

When the aqueous solution of GA is saturated with *n*-undecane, the temperature dependencies

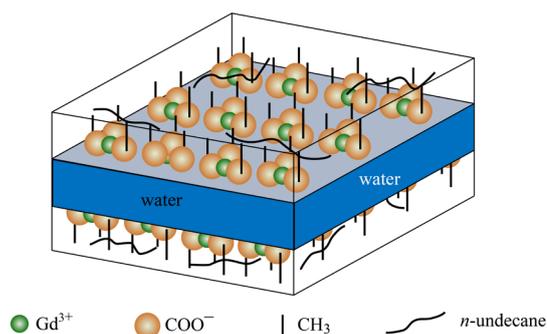


Fig. 1. Lamellar micelle (liquid crystal) in the GA–water–*n*-undecane system.

of the specific inverse magnetic susceptibility $\chi^{-1}(T)$ indicate the appearance of magnetic ordering of another type. The projection of the function $\chi^{-1}(T)$ on the abscissa axis is positive. This indicates that the ferromagnetic order is typical for metallic gadolinium. Figure 2 shows the temperature dependence of the specific inverse magnetic susceptibility for liquid crystals of the GA (0.1 M)–water–*n*-undecane system. In this case, the approximate linear function is:

$$\chi^{-1}(T) = 2.5 \cdot 10^5 T - 2.5 \cdot 10^7.$$

When comparing the magnetic properties of Gd^{3+} ions in a quantum material and with organized ions of liquid crystal, we can conclude that they are different. Using the classical theory of the formation micelles in water, they possess the structure of a hydrocarbon core with a double electric layer of ions. The double electrical layer consists of an adsorption layer and a diffuse layer. The ions of the adsorption layer are dense and organized. Based on such an organization of magnetic ions in the adsorption layer, we can rightly expect a strong exchange interaction between them with the manifestation of ferromagnetic properties. However, we observed the paramagnetic properties of gadolinium ions with random motion in solution.

Table. Specific magnetic susceptibility of GA aqueous solutions without micelles and with SDS spherical micelles at 298 K

Aqueous solutions	GA concentration, [M]	$\chi \cdot 10^{-7}$, [m^3/kg]
GA	0.0005	–6.0
GA	0.005	–4.0
GA	0.05	–1.8
GA + SDS (1:1)	0.0005	–4.0
GA + SDS (1:1)	0.005	–2.1
GA + SDS (1:1)	0.05	2.0

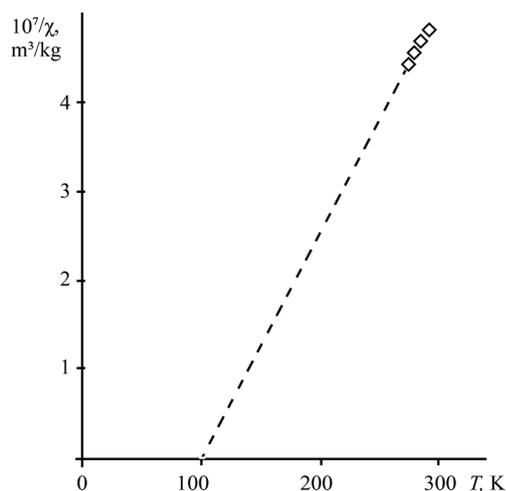
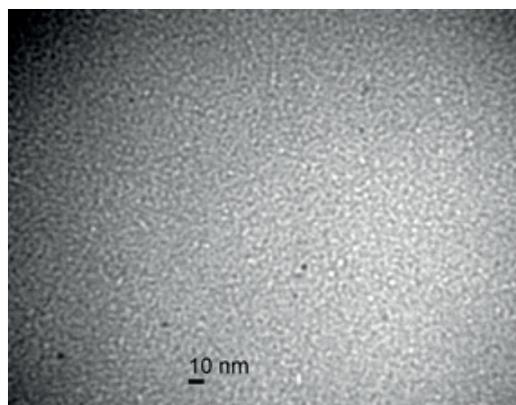


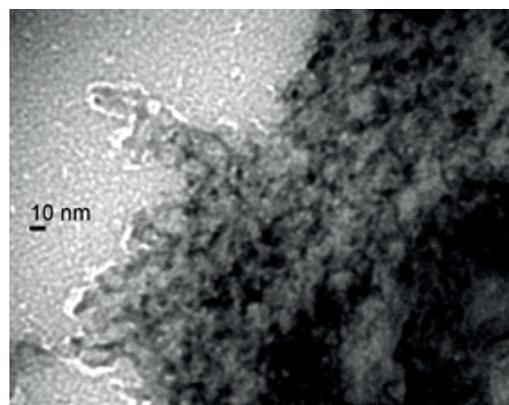
Fig. 2. Inverse magnetic susceptibility vs temperature for the lamellar micelle of the GA (0.1 M)–water–*n*-undecane system.

Magnetic properties of Pt–Gd nanoparticles obtained in a quantum material with cetylpyridinium chloride (CPC)

For the synthesis of hybrid nanoparticles, we chose $\text{H}_2[\text{PtCl}_6]$ and $\text{Gd}(\text{CH}_3\text{COO})_3$ with CPC concentration of 0.0293 M. This is greater than critical micelle concentration (CMC) = 0.002 M [18]. We passed nitrogen through the mixture of dissolved substances, in order to remove dissolved oxygen, followed by stirring. A yellow solution was obtained, the color of which is due to the interaction of the cetylpyridinium⁺ ion with $[\text{PtCl}_6]^{2-}$. The ions in micellar solution and alkaline medium were reduced with hydrazine hydrate. After reduction, a dispersion with dark brown nanoparticles was obtained, represented by the TEM image in the middle (Fig. 3a) and along the edges of the dried suspension (Fig. 3b).



(a)



(b)

Fig. 3. TEM images of hybrid Pt–Gd nanoparticles obtained in a quantum material and dried on a graphite substrate.

The content of Pt in the washed dry nanoparticles corresponded to the complete reduction of ions, 2.4 wt % Pt. The 82% content of Gd instead of 97.6% indicates the presence of organic impurities in the nanoparticles. These can be assumed to be CPC molecules. As can be seen from Fig. 3, the nanoparticles are 5–10 nm in size. The nanoparticles are self-organized in the quantum material (Fig. 3a) and this organization is visible in the dried material on the carbon substrate (TEM). The granular equidistant structure of the hybrid nanoparticles is also clearly visible. After the redox reaction and preparation for TEM, nitrogen and water disappeared from the reaction mixture, thus it can be assumed that the hybrid nanoparticles are distributed between CPC molecules.

In order to understand and compare this with our magnetic nanoparticles, we have presented the mechanism of photoreduction of Au and Pt ions in a micellar solution of SDS without the addition of a chemical reducing agent. Such a research method avoids pollution of the production of nanoparticles by reaction products and makes the study of the reaction mechanism purer. Micelles and nanoparticles have been investigated using small-angle X-ray scattering, extended X-ray absorption fine structure, and TEM [19]. The authors have provided evidence that SDS micelles are preserved with the inclusion of nanoparticles of the “nanoparticle core–surfactant shell” type. Au and Pt metal nanoparticles were formed photochemically in the cores of micelles, and had no significant effect on the micelle morphology. Before reduction, the ions were randomly distributed in solution, and after reduction, their reduced forms ended up inside micelles.

Our studies [8] have also proved the formation of condensation centers and magnetic nanoparticles

of manganese and cobalt in micelles. This behavior of ions indicates their participation in the quantum nuclear effect, as confirmed by our and other studies.

Let us compare the magnetic properties of crystalline Gd and powder Pt–Gd. According to reference data, the specific magnetization of bulk crystals Gd in a magnetic field 0.5–1.7 T in a nitrogen atmosphere is 240 A·m²/kg and bulk crystals has a Curie point of about 293 K. Specific magnetization of the synthesized powder Pt–Gd in a magnetic field 0.86 T is two orders of magnitude lower than those of Gd crystals and has the value 1.92 A·m²/kg. The Curie point of the studied Pt–Gd nanopowder is equal to ~270 K, which is ~23 K below the Curie point of the bulk sample. There is no blocking temperature on the ZFC curve which is typical for superparamagnetic nanoparticles.

Thus, taking into account the results obtained in the study of magnetic properties, it can be assumed that using such a synthesis method and without thorough purification of nanoparticles from surfactants, the Pt–Gd powder has an atypical magnetic behavior.

Magnetic properties of cobalt ferrite nanoparticles obtained in a quantum material with SDS

Cobalt ferrite nanoparticles were obtained by ion flotation extraction, in order to demonstrate the production of nanoparticles from waste using our integrated technology [20]. SDS were dissolved in a 1.5-liter solution, 0.0002 M CoCl₂ and 0.0004 M FeSO₄ and 0.0008 M. A micellar solution (quantum material) of a mixture of salts of cobalt, iron, sodium, and pink-colored SDS due to the presence of hydrated

cobalt ion is formed. After 10 min of ionic flotation extraction, the pink color of the aqueous solution disappeared: the mixture of toluene extractant with isoamyl alcohol turned pink. The extraction was stopped. After flotation, the extractant with iron cobalt salts and SDS was separated. The extractant was removed by distillation, the salt precipitate was dried under vacuum and over paraffin powder. Then the mixture of salts was treated with sodium hydroxide solution until complete precipitation of iron and cobalt hydroxides. This was washed with water and dried in air to obtain possible CoFe₂O₄. We deliberately did not shape the crystal lattice of CoFe₂O₄ by heating to thermally decompose SDS.

In order to obtain X-ray diffraction (XRD) and TEM images, the composite was preliminarily dispersed in ethyl alcohol using ultrasound. Received the dispersion was applied to a copper substrate coated with carbon. The diffraction pattern showed that the formation of the CoFe₂O₄ crystal lattice was either incomplete (i.e., the dense packing of the spinel structure was not formed) or a strongly defective structure was formed. This is indicated by slightly higher interplanar spacing and broadened diffraction peaks. Moreover, X-ray reflections are shifted towards larger angles, i.e., for a crystal cell with smaller parameters. Nanoparticles self-organize into a periodic colloidal structure on a carbon substrate (Fig. 4a) and have a maximum size distribution in the range of 4 to 6 nm (Fig. 4b).

Thus, the following conclusions can be drawn about the structure and magnetic properties of the formed nanoparticles. Surfactants adsorbed and included in the powder system interfere with the creation of an “ideal” crystal lattice of CoFe₂O₄.

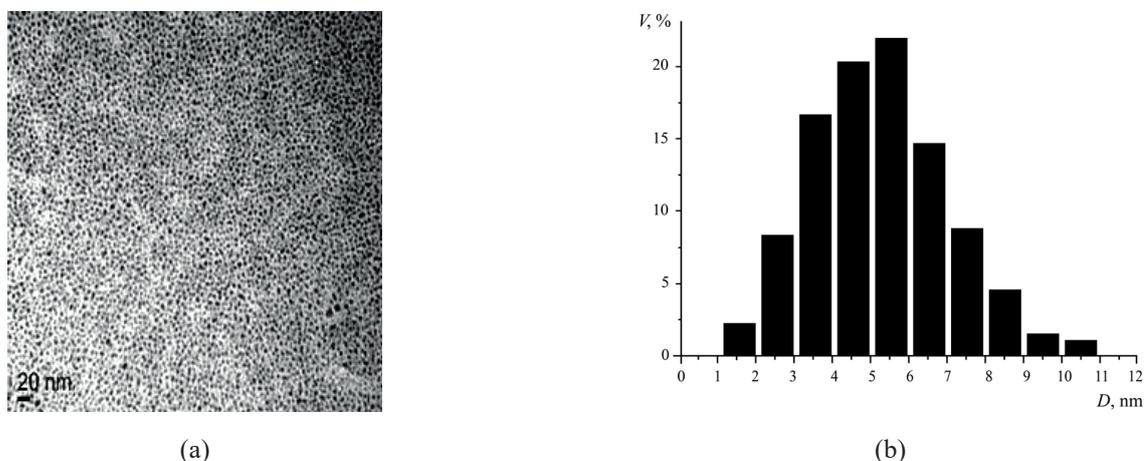


Fig. 4. TEM image of self-organization into a periodic colloidal structure of cobalt ferrite powder nanoparticles obtained in a quantum material and dried on a graphite substrate (a) and size distribution of nanoparticles (b); *V* is the relative frequency, %; *D* is the nanoparticle size, nm.

The particles consist of two components: a well-formed CoFe_2O_4 phase and its amorphous counterpart. Nanoparticles have a maximum size distribution in the range from 4 to 6 nm and self-organize into a periodic colloidal structure on a carbon substrate. As established from the ZFC–FC magnetization curves, the nanosized powder possesses a blocking temperature of 45 K with a magnetic moment of $0.85\text{--}0.9 \mu_B^2$ at a temperature of ~ 0 K, and the Néel temperature lies in the range of 110–250 K.

Magnetic properties of nickel ferrite nanoparticles obtained in a quantum material with SDS

The results of experimental elemental analysis of the synthesized powder of the expected nickel ferrite showed an increased content of iron and oxygen relative to stoichiometric nickel ferrite (NiFe_2O_4) [21]. The composition of the powder corresponds to $\text{NiFe}_{4.6}\text{O}_{14.8}$. The method described above for obtaining cobalt ferrite in the case of nickel leads to the formation of self-organizing nanoparticles of nonstoichiometric nickel ferrite (Fig. 5). This is because the synthesis process with the addition of alkali was accompanied by the partial removal of amphoteric nickel hydroxide. In addition, the resulting powder, in addition to iron and nickel hydroxides, possibly contained $(\text{C}_{12}\text{H}_{25}\text{SO}_4)_3\text{Fe}$, $(\text{C}_{12}\text{H}_{25}\text{SO}_4)_2\text{Fe}(\text{OH})$, and $(\text{C}_{12}\text{H}_{25}\text{SO}_4)\text{Fe}(\text{OH})_2$. They were difficult to isolate at the stage of filtering the precipitate after the addition of alkali. The 3% carbon content confirms such assumptions.

The XRD pattern of the synthesized powder had no sharp peaks; something which does not prove that ideal crystals were obtained. Elemental

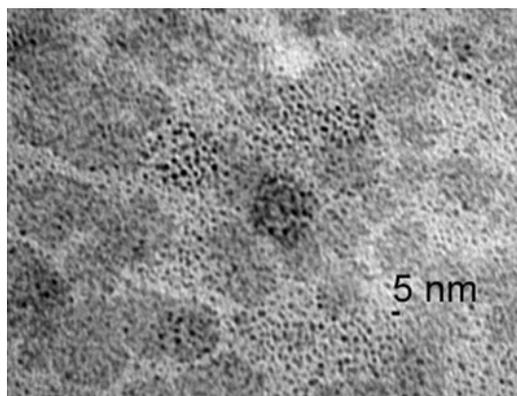


Fig. 5. TEM image of self-organization into a periodic colloidal structure of nickel ferrite powder nanoparticles obtained in a quantum material and dried on a graphite substrate.

$^2 \mu_B$ is the Bohr magneton.

analysis and XRD data of the powder convincingly prove that it consisted of X-ray amorphous non-stoichiometric ferrite and SDS. Furthermore, heat treatment at 600 °C caused the appearance of diffraction peaks of crystalline nickel ferrite.

The magnetic susceptibility of the material after ZFC or FC was measured [21, 22], in addition to standard magnetization versus magnetic field. In the ZFC procedure, the sample was cooled to 4 K without applying a magnetic field and measurements were made in a static magnetic field. Then the temperature was slowly raised and the magnetization was recorded. The FC procedure differed from the ZFC measurements only in that the sample was cooled in a non-zero magnetic field. FC and ZFC curves of magnetically inhomogeneous magnetic materials typically coincide at high temperatures while differing below their blocking temperature T_b . Their ZFC curves have a maximum at T_b , whereas their FC curves usually rise monotonically down to very low temperatures. At temperatures above $T_b = 25$ K, the synthesized nickel ferrite nanoparticles possess superparamagnetic properties (Fig. 6), characteristic of magnetic nanomaterials.

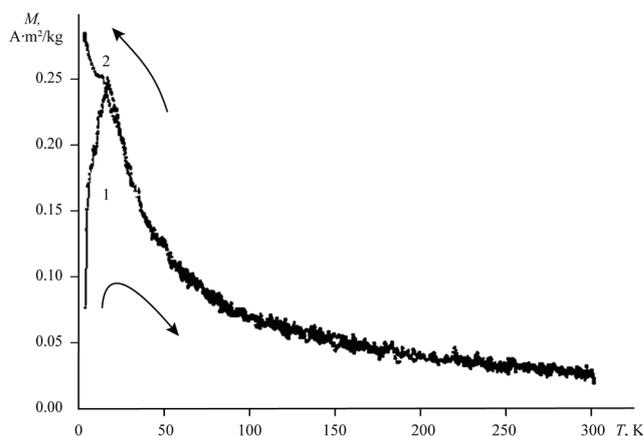


Fig. 6. Temperature dependence of the specific magnetization of nickel ferrite powder in magnetic field of 300 Oe: 1 – ZFC, 2 – FC.

Another important characteristic of a magnetic nanomaterial is its specific saturation magnetization. That of the synthesized ferrite nanoparticles is $15.0 \text{ A}\cdot\text{m}^2/\text{kg}$ at 5 K which is slightly below the saturation magnetization of bulk NiFe_2O_4 ($17.6 \text{ A}\cdot\text{m}^2/\text{kg}$).

From the experiment of synthesis of nanoparticles in a quantum material, the following conclusions can be drawn. It is possible to reduce metal ions of different signs of complex and simple $[\text{PtCl}_6]^{2-}$ and Gd^{3+} ions in a quantum material in a single step. This is very important when processing

waste to obtain nanoparticles of different metals [23, 24]. There are no differences in the recovery of supposedly “organized” ions of the adsorption layer and the diffuse layer of an ionic surfactant micelle. All ions are randomly distributed in the water quantum material.

The listed methods for the synthesis of nanoparticles were created in order to illustrate the production of nanoparticles from waste. This technology consists of three stages: firstly, aqueous solutions of simple or complex metal ions are obtained from waste; secondly, they are extracted by the method of ion flotation; at the third stage, ions are reduced to nanoparticles in an aqueous micellar solution.

Magnetic nanoparticles in a quantum material are necessary for their organization into long-range and dynamic assemblies on various substrates. Experiments show that nanoparticles in a quantum material self-organize well when dried on substrates in the second minimum of the dependence of their potential energy on distance. This technology will open up possibilities for a wide range of applications. In particular, materials can be created for which the remanent magnetization and coercive field are controlled at room temperature. For this, liquid crystals containing ions can also be used [25].

Self-organized structures are well-formed from dispersions of nanoparticles in a quantum material on any substrate. Further annealing on the substrate preserves this organization and allows the formation of a different mesoscopic order with emergent properties: an increase in the blocking temperature and the behavior of superspin glass [26, 27].

In terms of further potential, other emergent properties of quantum materials that can be used for the synthesis and application of magnetic materials found by other researchers may be a focus in the future.

Thus, there is an increase in the optical rotation of SDS solutions in the concentration range from 0.002 mol/L to CMC, followed by a decrease after CMC to a constant value at 0.015 mol/L and

higher [28]. The existence of a strong anisotropic structure around the CMC of ionic surfactants is confirmed [29]. Sonication increases the viscosity and solubilization in micellar solutions [30]. Interaction of quantum fluctuations of water with excitons of quantum dots with intense luminescence was established [30–32]. Films and foams obtained from surfactant solutions near CMC exhibit extreme properties [33].

CONCLUSIONS

Nano magnetic materials synthesized in aqueous micellar solutions of surfactants (aqueous quantum materials) exhibit emergent properties. This opens up the possibility of reducing ions of different signs in a single stage during the processing of metallurgy waste, in order to obtain nanoparticles of various metals and their composites. Magnetic nanoparticles obtained in a quantum surfactant material self-assemble on various substrates, enabling the creation of materials whose residual magnetization and coercive field can be controlled at room temperatures.

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Authors' contributions

Yu.A. Mirgorod – analysis and generalization of the results of studying the behavior of magnetic nanoparticles obtained in micellar solutions of surfactants.

N.A. Borsch – planning an experiment on the synthesis of magnetic nanoparticles in micellar solutions of surfactants.

A.M. Storozhenko – characterization of magnetic nanoparticles.

L.S. Ageeva – synthesis of magnetic nanoparticles in micellar solutions of surfactants.

The authors declare no conflicts of interest.

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