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THE INVESTIGATION OF INTERACTION OF SUPERCONDUCTING OBJECTS WITH LOW MAGNETIC FIELDS

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The paper is devoted to investigation of high-temperature superconductors (HTSC) and the superconducting casings interaction with low magnetic fields including those of nature origin. We investigate the interaction of superconducting objects of small average density until $3\cdot10^{-4}$ g/cm^3 which was ideal diamagnetic. The results of investigations of HTSC interactions with low magnetic fields were included the experimental data in 3D-diagrams in *F- P/V – H* coordinate*s*, which described the spreading regions of effective interaction observation in the direction of reduction of magnetic fields intensity.
KEY WORDS: high-temperature superconductors, Meissner effect, interaction, low magnetic fields, 3D-diagrams

ДОСЛІДЖЕННЯ ВЗАЄМОДІЇ НАДПРОВІДНИХ ОБ'ЄКТІВ ЗІ СЛАБКИМИ МАГНІТНИМИ ПОЛЯМИ

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Стаття присвячена дослідженню взаємодії високотемпературних надпровідників (ВТНП) і надпровідних оболонок зі слабкими магнітними полями, включаючи поля природного походження. Досліджено взаємодію надпровідних об'єктів(з найменшою середньою щільністю $3\cdot10^{-4}$ г/см^3), що є ідеальними діамагнетиками. Результати дослідження взаємодії ВТНП із низькими магнітними полями містять у собі експериментальні дані у вигляді 3D-диаграмм у координатах *F- P/V – H*, які описують розширення діапазону спостереження ефективної взаємодії надпровідних об'єктів у напрямку зниження напруженості магнітних полів.
КЛЮЧОВІ СЛОВА: високотемпературні надпровідники, ефект Мейсснера, взаємодія, низькі магнітні поля, 3D-діаграми.

ИССЛЕДОВАНИЕ ВЗАИМОДЕЙСТВИЯ СВЕРХПРОВОДЯЩИХ ОБЪЕКТОВ СО СЛАБЫМИ МАГНИТНЫМИ ПОЛЯМИ

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Статья посвящена исследованию взаимодействия высокотемпературных сверхпроводников (ВТСП) и сверхпроводящих оболочек со слабыми магнитными полями, включая поля природного происхождения. Исследовано взаиодействие сверхпроводящих объектов (с наименьшей средней плотностью $3\cdot10^{-4}$ г/см^3), являющихся идеальными диамагнетиками. Результаты исследования взаимодействия ВТСП с низкими магнитными полями включают в себя экспериментальные данные в виде 3D-диаграмм в координатах *F- P/V – H*, которые описывают расширение диапазона наблюдения эффективного взаимодействия сверхпроводящих объектов в направлении понижения напряженности магнитных полей.
KEY WORDS: высокотемпературные сверхпроводники, эффект Мейсснера, взаимодействие, низкие магнитные поля, 3D-диаграммы

The discovery of ceramic high-temperature superconductors (HTSC) and development of "know-how" HTSC have given ample opportunities in realization of magnetic levitation and magnetic hanging of the objects (magnets or superconductors) in magnetic fields [1]. High-temperature superconductor interaction with low magnetic fields is of great importance for experimental demonstration of physical body's levitation in low magnetic fields. It is known, enough weak magnetic fields don't penetrate to the thickness of ideal superconductor (Meissner Effect). Formally, under Meissner effect the magnetic susceptibility of superconductor is equal to $\chi = -1/4\pi$ as in the case of ideal diamagnetic. For example, in common diamagnetic substances $\chi = -(10^{-4} - 10^{-5})$ [2]. Therefore superconductors are the diamagnetic with spontaneous currents. Meissner effect is showed in the repulsive interaction with external magnetic field. This interaction depends from parameters of spontaneous currents and their distribution on surface layer. The phenomenon of superconducting and magnetic objects levitation in enough strong exterior magnetic fields (from 100 - 200 Oe and higher) is well known. The opportunity of the experimental observation and practical use of superconducting object levitation in low exterior magnetic fields quantity 0.5 – 2 Oe (geomagnetic fields) is less obvious in view of technological and technical difficulties. It is well known, that one of the elements of the «magnet - superconductor» system can steady levitate above the surface of the other element. The vertical elevating force occurrence usually explains displacement of the magnetic field from the volume occupied by the superconductor (ideal diamagnetic), due to Meissner effect. In recent articles the information about new devices including micro robot MEMS (Microelectronic Manipulation System) with m=0.83 g which may moving in 3D space is very fruitful [3].

The aim of this paper is the principle investigation of HTSC and the superconducting casings interaction with low magnetic fields including those of nature origin. The results of the research of hollow spheres and topologically connected objects with super conducting HTSC covering interaction with a weak geomagnetic field are given.

THE BASIC PRINCIPES OF SUPERCONDUCTORS INTERACTION WITH MAGNETIC FIELD

At the analysis of system diamagnetic object - magnet except for vertical component of elevating force F_z both the balance of forces in a cross-section direction and cross-section displacement force definition F_x are also of great importance. In similar experiments the magnet follows the superconductor (or vice versa) [4-7]. The capture of the part of the magnetic stream by a superconductor results in power interaction of objects (similarly to friction). In a concrete case for intensity H_e=1.3 кGs force of cross-section displacement achieves 5.1μN, and dependence of force of cross-section displacement on force of horizontal displacement shows a hysteresis of force, i.e. counting upon a field of intensity 1 Gs the cross-section component of force will make up shares of a dyne. Thus, observation of superconductor interaction with weak magnetic fields (WMF) intensity of several oersteds or shares of oersted (Oe) in principle is possible. The magnetic field of the Earth (geomagnetic field) is considered weak and changes from 0.24 Oe (Brazil) up to 0.68 Oe (Antarctica) and 2.7Oe (magnetic anomaly), on the average making 0.5 Oe.

Actually, the works on HTSC suspension in weak magnetic fields are practically absent. It is experimentally shown, that in the field of weak magnetic fields H< 10 Oe magnetization dependence strong deviation $M(H)$ from the linear law with a hysteresis in this area is observed [8]. The effect of nonlinear behavior decreases with growth of temperature. The more super conducting phase volume fraction was the more parameters of nonlinearly $M(H)$ appeared that could result in presence of a maximum in dependence $M(H)$. Similar nonlinear effects can influence the levitating object behavior in weak magnetic fields. Hysteresis phenomena and strong, thermally activated impulses of magnetic stream are characteristic for HTSC, in general [9]. As HTSC belong to 2nd order superconductors and have low value of first critical field $H_{c1}\approx$100 Oe (at 77 K) the suspended samples in such and big fields are in mixed conditions, the magnetic field penetrates into a sample as separate whirlwinds. It also witnesses of more effective HTSC suspension in weak magnetic field. Let us come back to estimations of HTSC levitation. For the sample levitating abilities characteristics interaction force ratio F with constant magnet field to the sample weight depending on distance was measured. Value F/mg is much more in textured samples in comparison with ceramics. In [10, 11] the some problems of superconducting spheres suspension in magnetic field 1000 Gs of one-turn superconducting coil was solved. For this purpose the simple estimation of pressure was used as the result of Meissner effect made 4 kPa. In the field 1000 Oe product of sphere radius by density $r\cdot\rho$ =300 kg/m^3=30 g/cm^3.Hollow Al spheres of 1.9cm in diameter, weight 2.5g get average volume density of 0.69 g/sm^3. Such spheres will be supported by the field of 140 Oe and are magnetic screens of internal volume. Use of superconductors for creation of magnetic screens also is based on Meissner effect. The residual magnetic field is kept inside of the magneto protected volume which can be lowered to 10^{-8} Oe in volume by well-known methods (transition in a superconducting condition in the field small in comparison with geomagnetic, the use of the unfolding screens, etc.). The other way of levitating objects creation (magnet weight 50 g, loss of weight - 2 %) consists in realization of the idea of the device on the basis of the rotating superconducting ceramic ring established on magnetic support (speed up to 5000 rev/min) has not yet found the confirmation after the message [12].

In [13] dependence of the measured elevating force is submitted the magnet height center above the surface of a superconducting disk of $YBa_2Cu_3O_7$, showing also hysteresis at rise and lowering. The increase of the HTSC-disk thickness increases the height of the suspension. It coordinates to next results. The method of the magnet suspension regulation height (weight 103.8 g) above the high-temperature superconducting disk (thickness of 8.5 mm and diameter 76 mm) is advanced. For the height regulation in magnetic system (magnet - HTSC) an additional field adjustable in value (50 - 80 Gs) is added which allowed to increasing approximately 20 times above the height of the magnet suspension. The opportunity of interaction force regulation can widely be used in magnetic support, magnetic suspensions, may be used for development of new types space vehicles. Such interaction in the mode of levitation has its own peculiarities. It is shown, that the force of interaction of two superconducting coils equal $F = F_d + F_t + F_i$, where F_d - diamagnetic, F_t - transport, F_i - inductive components. Coils interaction without taking into account superconductivity and for the case of massive superconductors it is possible not to take it into account cause transport force. Diamagnetic force defined by superconducting volume is negative and equal $F_d = \int gradB^2 dV$. Force F_i is also negative and caused by ideal conductivity effect of the superconducting coil. On the other hand, it is emphasized, that at interaction of tablets HTSC pressed different conditions with an external magnetic field, Meissner effect maximal contribution is more than the order less of the contribution of the whirlwinds congestion interfering penetration of the field. The surface (Bin - Livingston) barrier created by the surface defects prevents the arisen whirlwinds to enter the superconductor.

The first attempt to use superconducting microscopic objects levitation in low magnetic field (a magnetic field of the Earth in the near-earth space) was the proposition on the radioactive waste burial in space [14-23]. The theoretical and experimental investigations are shown that in space the interaction of superconducting particles with magnetic field of the Earth and solar wind plasma are effective. Acceleration of the charged micro particle appears is about $a_Q = 10^3$ cm/sec^2. Observation of dynamics (changes) of cloudy formations, fibers and other plasma structures in tails of comets detects significant acceleration of substance which it is impossible to explain without attraction of interaction of dust micro particles with a solar wind. Observable acceleration of dust tails of comets 2-3 order exceed the acceleration, caused by pressure of a sunlight and are being explained in view of the above-stated calculations by interaction of a solar wind with the charged micro particles. Thus, besides micro particles movement parameters estimation, there is an opportunity to estimate electric fields intensity in dust tails of comets. The order of speeds of the dust tails received due to influence of a solar wind varies in limits $(2 \div 25) \cdot 10^6$ cm/sec. As a result of the numerical analysis of astrocindery particles dynamics and their interaction with magnetic field of the Earth and solar wind plasma it is shown, that from the considered mechanisms the most essential is interaction of the charged micro particles with a solar wind. The acceleration value due to such interaction can exceed the values caused by photon pressure on 2-3 order [22, 23].

THE RESEARCH OF HOLLOW SPHERES WITH SUPER CONDUCTING HTSC COVERING INTERACTION WITH A WEAK MAGNETIC FIELD

In this chapter we present experimental results. In Fig.1 we represent the 3D diagram in coordinates *P/V – H - F/P* from literature values which described in previous chapter. Some experimental details are described in [24]. The results of experiments are resulted in Fig. 2-6. At studying levitation of diamagnetic in magnetic fields the experiments on pushing out diamagnetic, in our case super conducting bodies from a constant magnetic field, are more often carried out. The suspension will be steady, a sphere or a cylinder shape object is chosen. The variant of the object (with HTSC covering) suspension in a geomagnetic field is the most interesting. The resulted data illustrate the opportunity to create superconducting objects, interacted with weak magnetic fields. We are prepared hollow spheres with superconducting coating of various average densities (until to $3 \cdot 10^{-4}$ g/cm^3. This objects handing in geomagnetic field and we determine as absolute values of lifting force F (with precision $5 \cdot 10^{-5}$ g) as and relative values F/mg =ΔP/P (in arbitrary units) depending on the relative elevating density of the objects. For measurements balance and the method of misbalance were used. Microcrystalline powders were deposited on the surface of spheres and other typologically mono coherent objects. Superconducting phase content made 95 % and was supervised by diamagnetic response observation in strong (up to 2 кOe) magnetic fields. Then the researched object is located on the low temperature stand for measurement of expulsive force F . The experimental temperature curve of electrical resistively of $YBa_2Cu_3O_{7-X}$ sample is shown in Fig. 2. The content of superconducting phase (in table) is controlled by determination of diamagnetic response in strong magnetic fields (until to 2 kGs). Image of superconducting object with average density 0.08 g/cm^3 is shown in Fig. 3.

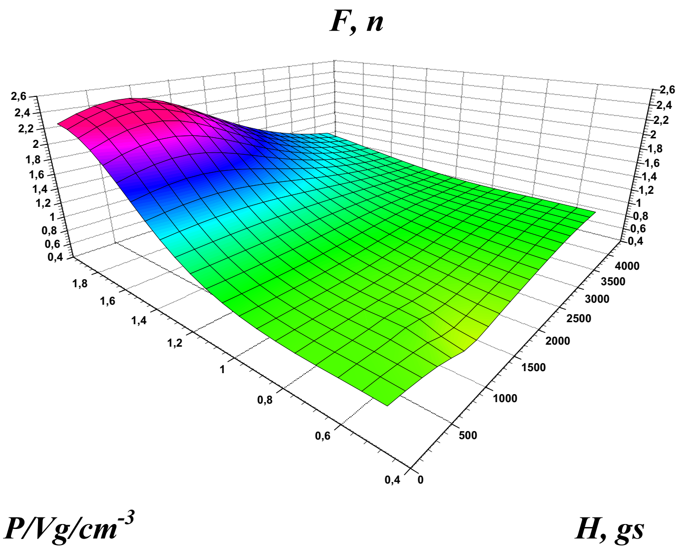

Fig. 1. The 3D diagram in coordinates *P/V – H - F / P* from literature values

Table. Content of doping in the ceramic $YBa_2Cu_3O_{6,85}$

Element	Content, wgt. %
Fe	0.0014
Si	0.003
Al	0.009
Mg	0.0002
Pb	0.0015
Mn	0.00005
Ni, Cr	<0.0005
Mo, V, Co	<0.0005
Sn	<0.0002

According to [25] on a superconductor in magnetic field expulsive force (on an individual element of a surface) operates:

$$F = \sigma_{ik} n_k, \tag{1}$$

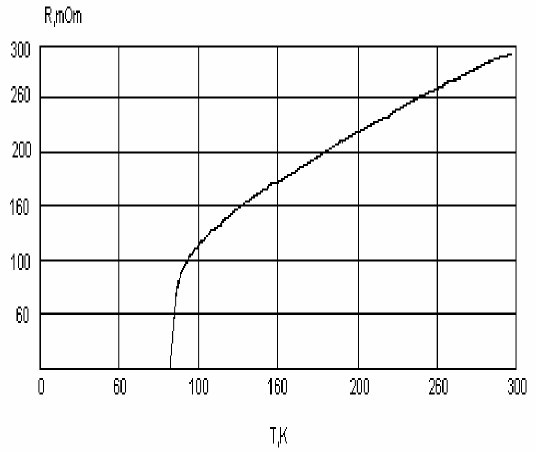

Fig. 2. The experimental temperature curve of electrical resistivity of $YBa_2Cu_3O_{7-x}$ sample

Fig. 3. Image of superconducting object with average density 0.08 g/cm^3

here $\sigma_{ik} = \frac{1}{4\pi}\left(H_i H_k - \frac{H^2}{2}\delta_{ik}\right)$ - stress tensor for magnetic field in vacuum. If $\vec{n}H_e = 0$ (H_e -an external magnetic field), we put

$$\vec{F} = -\vec{n}\,\frac{H_e^{\,2}}{8\pi} \qquad (2)$$

Thus pressure on an individual element of a surface of a superconducting object equals:

$$F = -\frac{H_e^{\,2}}{8\pi}\,. \qquad (3)$$

Experimental data are presented in Fig. 4 as the experimental relation between lifting force (lnΔP/P) = ln (F/P) and volume density (P/V) for objects with surface superconductor layers. In Fig.5 the experimental data are presented as 3D diagram in coordinates P/V – H - F / P which based on the experimental values the relation between lifting force ΔP/P) = F/P and volume density P/V of objects with surface superconductor layers. Dependence, despite of variability of data, specifies essential reduction of the expulsive force registered specifies essential increase of levitation force for the objects with minimally achievable volumetric density. These results confirm a reality of registration and probable practical use of the super conducting "bubbles" emerging in a geomagnetic field.

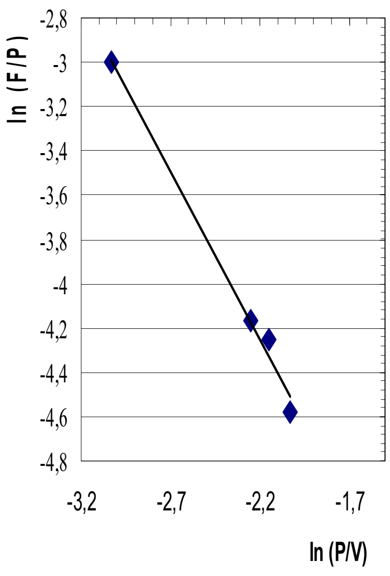

Fig. 4. The experimental relation between lifting force (ln ΔP/P) = ln (F/P) and volume density (P/V) of objects with surface superconductor layers

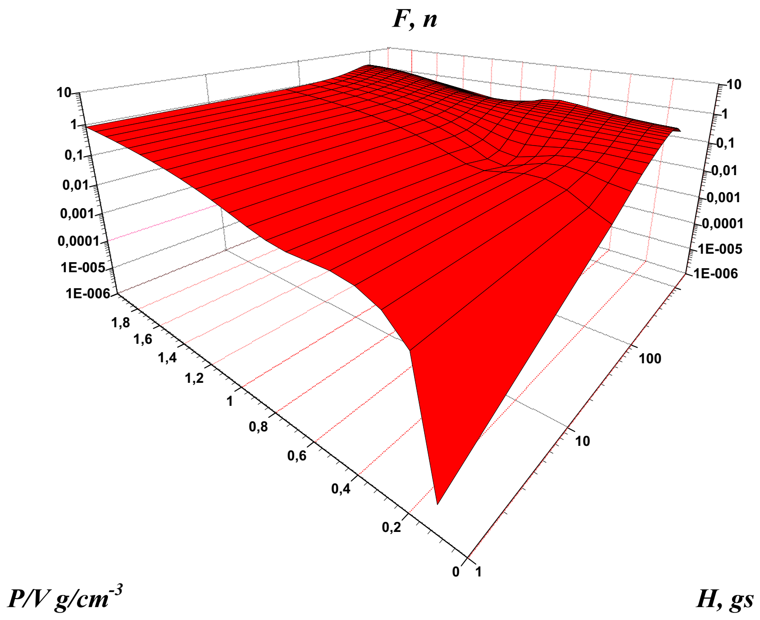

Fig. 5. The 3D diagram in coordinates *F - P/V – H* on the base of experimental values

We compare experimental data with the results of estimated calculations. As is known, the force $\vec{F}$ working in a magnetic field with an induction $\vec{B}$ on a diamagnetic body of individual volume with relative magnetic permeability μ is defined by value:

$$F = \frac{1-\mu}{2\mu_0} \cdot \frac{\partial B^2}{\partial z}, \qquad (4)$$

where $\frac{\partial B^2}{\partial z}$ - induction square gradient in vertical direction. The body can freely hang in a weight field provided:

$$F \geq \rho \cdot g \text{ , } or \frac{\partial B^2}{\partial z} \geq \frac{2g\mu_0\rho}{1-\mu}. \qquad (5)$$

Of traditional diamagnetic in the condensed condition the least value $\rho(1-\mu)$ has graphite ($2.3\cdot10^7$ kg/m^3) [26]. For graphite it is necessary $\frac{\partial B^2}{\partial z} \geq 5.7\cdot10^2$ Тл^2/м for superconductors, in particular, HTSC such as Y-Ba-Cu-O of $\rho(1-\mu)$ has minimum value. Thus, and by these estimations ideal diamagnetic suspension and levitation (HTSC) in weak magnetic fields (the order of oersted) is possible and observe experimentally. We are obtained the satisfactory agreement of such estimations with experimental data. For example, in the magnetic field value such as 0.5 – 1 Oe we obtain an estimation value of lifting force as 10^{-4} $4\cdot10^{-4}$ n in compression with average experimental value $2\cdot10^{-4}$ n.

Thus, at registered interaction HTSC of objects with a geomagnetic field it is necessary to take into account and use:

- non-linear and hysterics effects,
- opportunity to regulate and amplify interaction force due to additional magnetic field,
- the necessity of the detailed studying of the mechanism of an external magnetic field penetration into HTSC of various structure,
- the analysis of interaction in system "diamagnetic - magnet" for various components of elevating force and magnetic fields,
- observation of superconductor interaction with weak magnetic field of the Earth (geomagnetic field) in various geographic points which values considered weak and changes from 0.24 Oe (Brazil) up to 0.68 Oe (Antarctica) and 2.7 Oe (magnetic anomaly).

Thus, observation of superconductor interaction with weak magnetic fields (intensity of several oersted or shares of oersted) is possible. Another perspective of improved interaction of HTSC with low magnetic fields will be using as casing the new carbon materials – grapheme [27] on the base of impermeable atomic membranes from grapheme [28].

CONCLUSIONS

We study the fundamental principles of interaction of superconducting shells and particles in weak magnetic fields and we will determine the physical mechanism which responsible for these effects. We obtain superconducting objects and shells interacted with weak magnetic fields. Characteristics of the obtained objects with superconducting coating on 20-30% higher compared to materials of corresponding composition. We obtain composites on the base of high temperature superconductor ceramics (with T_c = 90-93 K) as hollow with superconducting coatings, which will ensure their heat resistance in the air medium. We demonstrate the possibility of effective interaction of superconducting objects of small average density until to 10^{-4} g/cm^3 with low magnetic fields (0.5 Gs).

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