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Peculiarities of phase transitions in the Josephson medium of the granular high-temperature superconductors $YBa_2Cu_3O_{7-\delta}$ under the influence of temperature, external magnetic field, and transport current

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The work is devoted to establishing the identity of the topological phases arising in the Josephson medium of granular high-temperature superconductors $YBa_2Cu_3O_{7-\delta}$ during the Berezinskii-Kosterlits-Thouless phase transitions (BKT transition) under the influence of an external magnetic field and transport current. It has been established that the nature of the topological phases arising as a result of the BKT phase transition does not depend on the type of external influence.
Keywords: High-temperature superconductors, phase transition, topological phases.

Особливості протікання фазових переходів у джозефсонівському середовищі гранулярного високотемпературного надпровідника $YBa_2Cu_3O_{7-\delta}$ під дією температури, зовнішнього магнітного поля і транспортного струму *Т.В. Сухарева, В.О. Фінкель, В.В. Дерев'янко*

Робота присвячена встановленню тотожності топологічних фаз, що виникають в джозефсонівському середовищі гранулярних високотемпературних надпровідників $YBa_2Cu_3O_{7-\delta}$ при протіканні фазових переходів Березинського-Костерлиця-Таулеса (ВКТ-перехід) під дією зовнішнього магнітного поля і транспортного струму. Встановлено, що характер топологічних фаз, які виникають в результаті БКТ фазового переходу, не залежить від виду зовнішнього впливу.

Работа посвящена установлению тождественности топологических фаз, возникающих в джозефсоновской среде гранулярных высокотемпературных сверхпроводников $YBa_2Cu_3O_{7-\delta}$ при протекании фазовых переходов Березинского-Костерлица-Таулеса (ВКТ-переход) под действием внешнего магнитного поля и транспортного тока. Установлено, что характер топологических фаз, возникающих в результате БКТ фазового перехода, не зависит от вида внешнего воздействия.

1. Introduction

In 2016, the Nobel Prize in Physics was awarded to John Michael Kosterlitz, David Thouless and Duncan Haldane with the wording "for theoretical discoveries of topological phase transitions and topological phases of matter". From the wording of the decision of the Nobel Committee in 2016, it follows that the prize was awarded exclusively for theoretical work in the field of establishing the nature of topological phase transitions and topological phases of matter. Naturally, the theory contains a set of sufficiently important markers for the possible detection of topological phase transitions, in particular, the Berezinskii-Kosterlitz-Thouless (BKT-phase transitions) transition, the most important of which is the reduced dimension of systems (1D or 2D), in which the occurrence of such phase transitions is potentially possible [1-4]. The basis of our experimental studies on the discovery and establishment of the nature and mechanisms of topological BKT phase transitions and topological phases is the idea that the Josephson medium of two-level granular high-temperature superconductors, whose topology can be controlled by temperature, an external magnetic field, and/or transport current [5], can serve as an optimal two-dimensional object, in which topological BKT phase transitions can be detected and reliably identified using measurements of electromagnetic properties.

As is known, a description of the behavior of granular high-temperature superconductors (HTSC) in an external magnetic field is possible within the framework of a two-level model of the critical state [6, 7]. In the framework of this model, granular HTSCs are considered as a combination of two subsystems of superconductors of the second kind [8]: three-dimensional superconducting granules with strong superconductivity and two-dimensional intergranular boundaries Josephson "weak links" with weak superconductivity.

In the framework of the two-level model for superconducting granules (grains) [indices "g" (grain)] and intergranular boundaries Josephson "weak links" (index "J"):

$$H_{c1g}(T)>H_{c1J(T)},\ H_{c2g}(T)>H_{c2J}(T), \quad (1)$$
$$I_{cg}(T,\ H_{ext})>>I_{cJ}(T,H_{ext}),$$

where H_{c1g} and H_{c1J} are the critical fields in the beginning of the process of penetration of the magnetic field into the subsystems of the granular superconductor; H_{c2g} and H_{c2J} are the critical fields for the total penetration of the magnetic field into the subsystems of the granular superconductor; I_{cg}, I_{cJ} are critical currents of superconducting granules and intergranular boundaries, respectively.

It would seem that the system of inequalities (1) adequately describes the processes of penetration of magnetic field into both subsystems of a two-level granular superconductor. The penetration of the external magnetic field H_{ext} into granular high-temperature superconductors is realized by means of Abrikosov vortices into granules at $H_{ext} > H_{c1g}$ and through Josephson vortices into "weak links" at $H_{ext} > H_{c1J}$ [9]. In this case, however, the question on the nature of the influence of the transport current density (j) on the critical parameters of granular HTSC is rather complicated. Two channels of the effect of the transport current on the critical temperatures and critical fields of superconducting granules and "weak links" are possible (see, for example, [10, 11]): a) by means of the magnetic field created by the current, and b) by the "direct" action of the current on the vortex structure of a two-level HTSC. It is almost obvious that the direct influence of the transport current can noticeably affect only the processes occurring in the Josephson medium (we are talking about the evolution of the system of "weak links", i.e. the appearance and movement of single "weak links", the appearance of their conglomerates and the formation of continuous Josephson contacts) [12].

The ultimate goal of the study is to establish the identity of the topological phases occurring by two fundamentally different scenarios of BKT phase transitions the effect of an external magnetic field and/or transport current on the Josephson medium of granular HTSCs. We believe that the coincidence of the H-T phase diagrams of the Josephson medium of granular HTSCs in the region of realization of BKT transitions according to the two different external exposure scenarios could serve as an adequate proof of the identity of the topological phases.

2. Methodological aspects

In this paper, the routines of experiments, processing experimental results, and analyzing data obtained according to two fundamentally different scenarios of possible topological phase transitions in a Josephson medium of two-level high-temperature superconductors were optimized using a continuous change in one parameter, a discrete change in another parameter, and a constant value of the third parameter.

Scenario 1: Studying the temperature dependences of the magnetoresistance $\rho(T,\ H_{ext})_{j=\mathrm{const}}$ at a constant value of the transport current density j (temperature T is a continuous parameter, external magnetic field strength H_{ext} is a discrete parameter, and transport current density j is a constant parameter) [13]. The nature of $H_{BKT}(T_{BKT})$ dependencies will be established.

Scenario 2: Studying the current-voltage characteristics (CVC) with a constant value of the external magnetic field strength, $E(T,\ j)_{H\mathrm{ext=const}}$ (temperature T is a continuous parameter, j is a discrete parameter, and H_{ext} is a constant

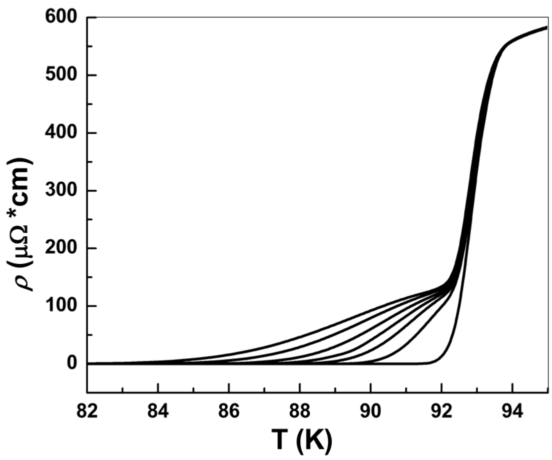

Fig. 1. Temperature dependences of electrical resistivity for $YBa_2Cu_3O_{6.95}$ granular HTSC in external magnetic fields. From bottom to top, H_{ext} = 0, 10, 25, 50, 100, 250, 500 Oe.

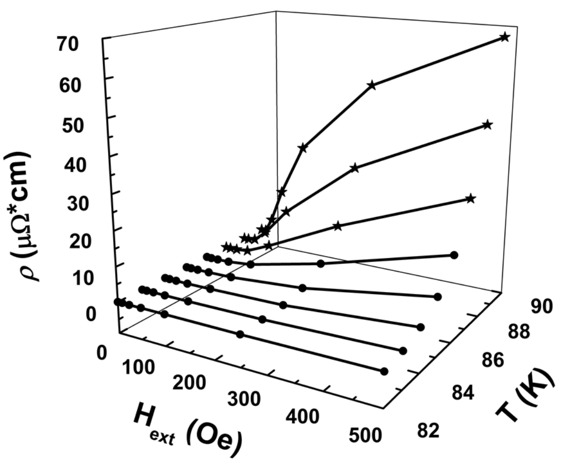

Fig. 2. Temperature dependences of magnetoresistance for $YBa_2Cu_3O_{6.95}$ granular HTSC. For clarity, only a part of the obtained magnetoresistance isotherms corresponding to integer values of the parameter T is shown.

parameter) [12,14]. The nature of $T_{BKT}(H_{ext})$ dependencies will be established.

The discrete parameters in the experiments should be changed over a sufficiently wide range; in our opinion, this will make it possible to detect topological phase transitions, both in the magnetic field and in the transport current: $0 < H_{ext} \le H_{c1g}$ and $0 < I \le I_{cg}$.

2.1. Objects of study

The objects of study were single-phase samples of granular HTSC $YBa_2Cu_3O_{7-\delta}$ of nominal composition $YBa_2Cu_3O_{6.95}$ synthesized according to the standard "ceramic technology". The sizes of the samples were ≈2x2x20 mm^3. Current and potential contacts were obtained by deposition of silver vapor in vacuum [15].

To certify the HTSC samples of $YBa_2Cu_3O_{6.95}$ composition, we used the methods of X-ray diffraction analysis (the values of the parameters of the rhombic crystal lattice within the measurement accuracy coincided with the tabulated values. a = 3. 82 ± 0.001 Å, b = 3. 89 ± 0.001 Å, c = 11.6802 ± 0.001 Å) [16], and resistive and magnetic measurements of the critical temperature (the temperature of the middle of the superconducting transition, $T_c^{1/2}$, determined from the maximum of the derivative $dp/dT(T)$, was 92.65±0.01 K, the transition width ΔT_c did not exceed 0.4 K.) [17, 18].

2.2. Experimental setup

To carry out electro-physical measurements in both of the scenarios described above, a special installation based on the RGD-210 Leybold cryogenerator (20 – 273 K) was developed and implemented; it was equipped with an external system of permanent magnets from the high-coercive $Nd_2Fe_{14}B$ alloy to create permanent magnetic fields of strength up to ~ 2000 Oe [19] (a similar method of creating a highly stable magnetic field in cryostats provides improved measurement accuracy [20]).

3. Results

3.1 Scenario 1. Magnetoresistance

In accordance with Scenario 1, the following research program was implemented:

1. Measurements of the temperature dependences of electrical resistivity under conditions of continuous temperature change (≈70≤ T≤100K) and discrete changes in the strength of an external perpendicular magnetic field ($0 \le H_{ext} \le 500$Oe) at a constant value of the transport current density (j = 2 A/cm^2).
2. Development and implementation of algorithms for converting the results of direct measurements of the temperature dependences of the electrical resistance at given external parameters (H_{ext}, j) into the set of magnetoresistance isotherms $\rho(H_{ext})_{T=const}$.

Fig. 1 presents the results of precision measurements of the temperature dependences of the electrical resistivity at fixed values of the strength of the perpendicular external magnetic field in the temperature range of 70≤ T≤ 95 K (to apply a magnetic field, the FC mode, cooling in a magnetic field was used. A similar regime, as shown previously [19], ensures the achievement of

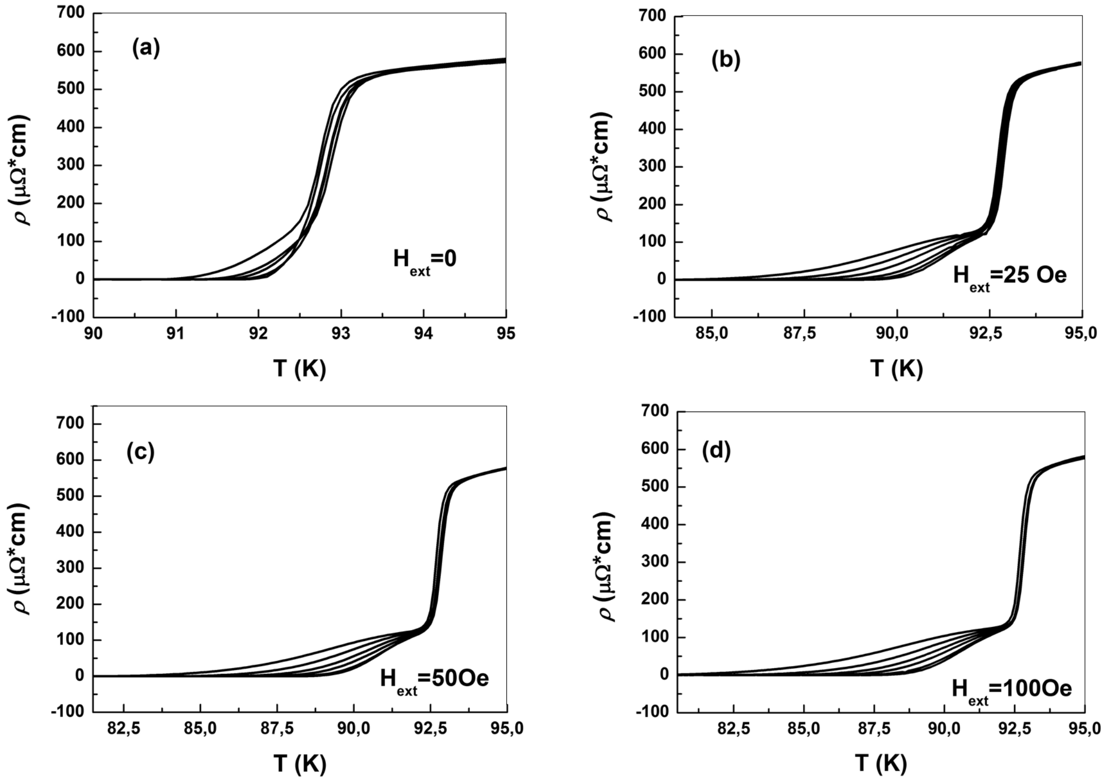

Fig. 3. Temperature dependences of electrical resistivity $\rho(T)$ at H_{ext} = 0, 25, 50, 100Oe; transport current density values are (from bottom to top): j = 50, 100, 250, 500, 1000 and 2000 mA/cm^2.

the maximum degree of equilibrium between the object of study – a granular HTSC and an external magnetic field; the achievement of the equilibrium was facilitated by use of very low cooling and heating rates for the samples (0.002–0.004 deg/s).), at a constant value of the density of the transport current. All the measurements were carried out under conditions of increasing temperature.

In accordance with the program described above, the results of direct measurements of the temperature dependences of the electrical resistivity, i.e. the matrix $\rho(T)H_{\text{ext=const}}$, was transformed into the matrix $\rho(H_{\text{ext}})_{T=\text{const}}$. In this regard, the obtained values of $\rho(T)_{H\text{ext=const}}$ were interpolated to specific temperature values with a "step" of 0.1 K. The results of data conversion $\rho(T)_{H\text{ext=const}} \to \rho(H_{\text{ext}})_{T=\text{const}}$ are presented in Fig.2.3.

As you can see, when the temperature changes, the behavior of the magnetoresistance curves changes fundamentally:

– in the range of $\approx 82 \le T \le \approx 86$K, the isotherms of the magnetoresistance are almost linear; this behavior of the magnetoresistance curves $\rho(H_{\text{ext}})$, obviously, eliminates the possibility of any other phase transitions besides a continuous phase transition at $T = T_{c2J} = T_{\rho=0}$ (the temperature of the full penetration of the magnetic field into the subsystem of Josephson "weak links", characterized by the appearance of resistivity); – in the range of $\approx 87 \le T \le \approx 89$K, the isotherms of the magnetoresistance are clearly anomalous: with increasing external magnetic field H_{ext}, the "high-temperature" isotherms $\rho(H_{\text{ext}})$ exhibit a sharp increase in resistance, a characteristic kink appears on the curves; after passing the inflection point, the magnetoresistance isotherms noticeably change the course.

3.2. Scenario 2. Current-Voltage Characteristics

In accordance with Scenario 2, the following research program was implemented:

1. Measurements of the temperature dependences of the electrical resistivity under conditions of continuous temperature change ($\approx 70 \le T \le \approx 100$K) and discrete changes in the transport current density ($50 \le j \le 2000$ mA /cm^2) at constant values of the external perpendicular magnetic field strength (H_{ext} = 0, 25, 50, 100 Oe).

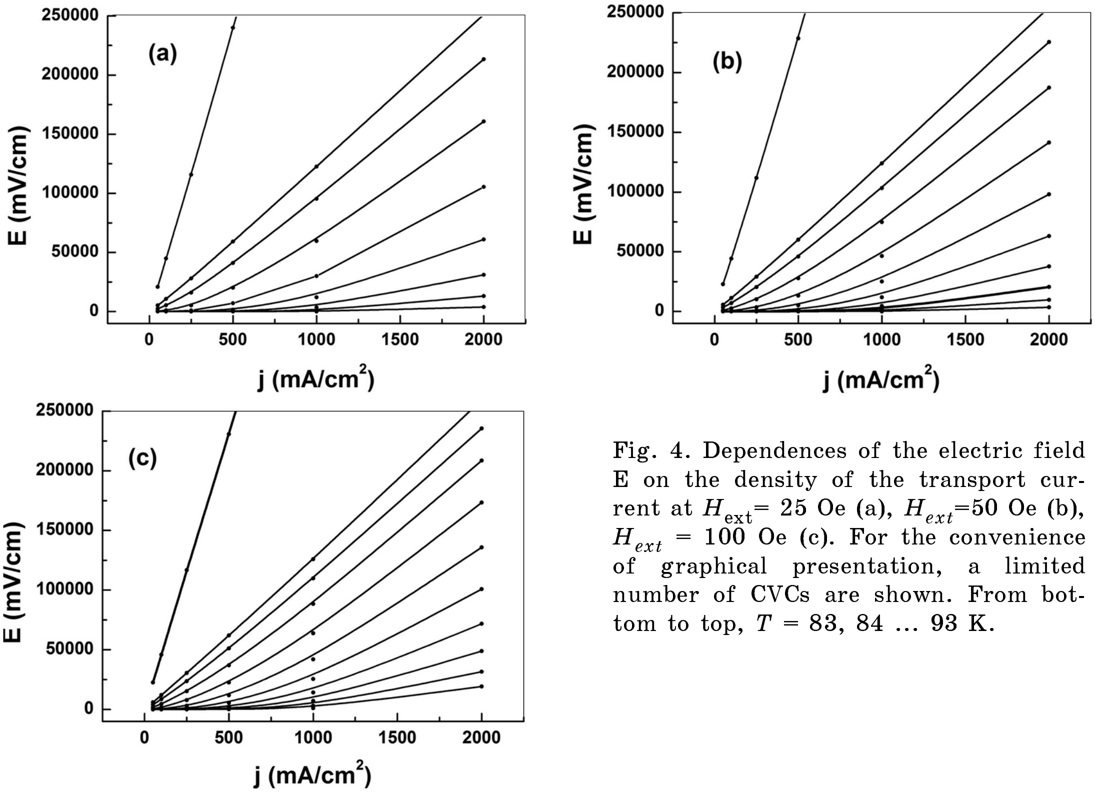

Fig. 4. Dependences of the electric field E on the density of the transport current at H_{ext}= 25 Oe (a), H_{ext}=50 Oe (b), H_{ext} = 100 Oe (c). For the convenience of graphical presentation, a limited number of CVCs are shown. From bottom to top, T = 83, 84 ... 93 K.

2. Recovery of the current-voltage characteristics (CVC) in a wide temperature range on the base of the obtained experimental data on the temperature dependences of the electrical resistance of granular samples of HTSC $YBa_2Cu_3O_{6.95}$.

Figure 3 shows the temperature dependences of the electrical resistivity ρ(T) for various values of j at constant values of the external perpendicular magnetic field strength H_{ext} = 0, 25, 50, 100 Oe. The absence of a maximum on the ρ(T) curves at H_{ext}= 0 is due to the almost complete absence of the subsystem of "weak links" in a zero magnetic field. The appearance of a maximum on the ρ(T) curves at $H_{ext} \neq 0$ is associated with a change in the dissipation mechanism – a high level of dissipation on "weak links" is replaced by a moderate level of dissipation on superconducting granules as a result of the redistribution of the magnetic flux between both subsystems of a two-level granular HTSC [5, 18].

In accordance with the research program described above, the result of direct measurements of the temperature dependences of the electrical resistivity the matrix $\rho(T)_{j=\mathrm{const}}$ was transformed into the matrix $E(j)_{T=\mathrm{const}}$. In this connection, the obtained values of $\rho(T)_{j=\mathrm{const}}$ were interpolated to specific temperature values with a "step" of 0.1 K. Figure 4 shows only a part of the isotherms E(j) obtained in this way at H_{ext} = 25, 50, 100 Oe. As can be seen, all the CVCs are obviously nonlinear with the exception of the dependences $E(j)_{T=93\mathrm{K}}$, i.e. at $T > T_c$.

4. Discussion

Before discussing the results obtained, it should be recalled that according to modern concepts (see, for example, [21]), the essence of the Berezinskii-Kosterlitz-Thouless topological phase transition consists in the transition from a high-temperature disordered phase with exponential correlation to a low-temperature quasi-ordered phase with a correlation function which decreases with distance according to a power law and depends on temperature. In other words, as shown by V.L. Berezinskii in priority works [1, 2], at low temperatures, the vortex and antivortex form a bound state – a vortex pair; and at sufficiently high temperatures, the pairs dissociate. Unlike dissociation in a three-dimensional gas, the two-dimensional dissociation is not carried out gradually, but by a phase transition at a certain temperature.

4.1. Establishment of the nature and behavior of magnetoresistance isotherms with *a change in temperature and intensity of an external magnetic field*

The first subject of discussion should be the appearance of the anomalies described above in the behavior of magnetoresistance isotherms with a change in temperature and external magnetic field strength (see 3.1). Obviously, the nature of the evolution of magnetoresistance isotherms with temperature changes carries information on the occurrence of topological phase transitions. Thus, there is every reason to believe that the anomalous behavior of the magnetoresistance isotherms (see Fig. 2) is due to the BKT phase transition by the magnetic field in the region of the existence of resistivity of the Josephson medium, $[H_{c2J}(T) - H_{c1g}(T)]$, in the granular HTSC $YBa_2Cu_3O_{7-\delta}$.

4.2. Establishment of the nature and features of the behavior of CVC parameters with a change in temperature and external magnetic field

In a number of theoretical and experimental works (see, for example, [22-28]), an analysis of the CVC behavior was used as the main method for detecting topological phase transitions. As is known (see, for example, [29-32]), in relatively weak magnetic fields, the current - voltage characteristic E(j) of granular HTSCs can be described, to a first approximation, by a semi-phenomenological power function:

$$E = A \cdot [j - j_c(T, H_{ext})]^{\nu}, \qquad (2)$$

where A is the proportionality parameter depending on the dissipative properties of the object under study; $j_c \equiv j_{cJ}$ is the critical density value of the Josephson current; ν is the CVC nonlinearity coefficient.

In Fig. 5, the dependences of the critical density of the Josephson current $j_{cJ}(T)$ for H_{ext}= 25, 50, 100 Oe, obtained in accordance with equation (2), are presented. It can be seen from the figure that, in a very narrow temperature range, there are pronounced jumps in the critical density of the Josephson current j_{cJ}. In this case, the effect of an anomalous decrease in the critical density of the Josephson current by several times takes place! At the same temperatures, characteristic jumps were found in the dependences of the proportionality parameters A(T) and in the nonlinearity coefficients ν(T) of CVC (Fig. 6, 7). Obviously, the observed effects of the jump-like change in CVC parameters (see Figs. 5, 6, 7) are

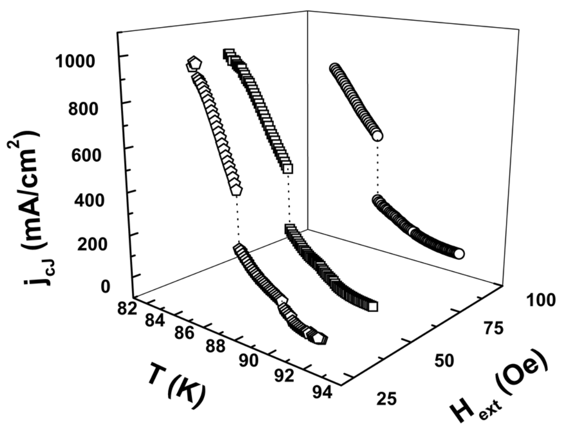

Fig. 5. Temperature dependences of the critical density of the Josephson current j_{cJ} in Eq. (2). Pentagons, squares, and circles correspond to H_{ext} = 25, 50, and 100 Oe.

associated with the BKT phase transition in the transport current $[I_{cJ}(T) - I_{cg}(T)]$ in the region where the resistivity of the Josephson medium exists in $YBa_2Cu_3O_{7-\delta}$.

4.3. Establishment of the identity of the topological phases arising as a result of BKT phase transitions under the influence of electric and magnetic fields

In the present work, it was first discovered that the appearance of all anomalies in the behavior of magnetoresistance isotherms (see 3.1, 4.1) and CVC parameters (see 3.2, 4.2), regardless of the magnitude of the external magnetic field strength and the density of the transport current, is localized in a strictly defined sufficiently narrow temperature range, namely, in the region of existence of Josephson medium resistivity, $T_{c2J}(T_{\rho=0})–T_{c1g}$. Moreover, it was shown that the positions of the anomalies on the temperature axis, determined for two fundamentally different types of external impact on the Josephson medium of the $YBa_2Cu_3O_{7-\delta}$ granular HTSC, coincide within the accuracy of the electrophysical measurements. However, the question remains open: does the proximity of the temperatures of the BKT transition found in the work testify to the identity of the topological phases arising under the influence of a magnetic field and a transport current? To get an answer to this fundamentally important question, an *H-T* phase diagram of the Josephson medium of granular HTSCs was constructed in the range of realization of BKT transitions proceeding according to the two external impact scenarios.

The data presented in Fig. 8 clearly indicate the almost complete identity of the

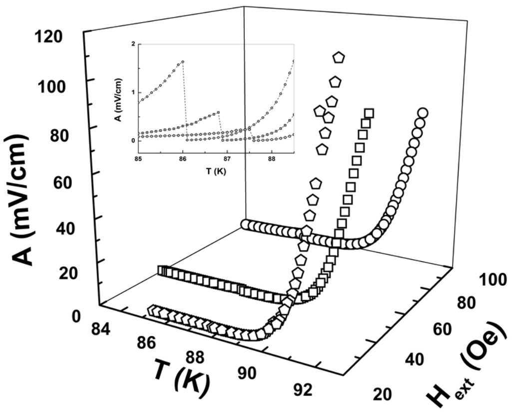

Fig. 6. The temperature dependences of the proportionality parameter A(T) in Eq. (2). The symbols are the same as in Fig. 5. The inset shows the temperature dependence of the proportionality parameter A in the jump region.

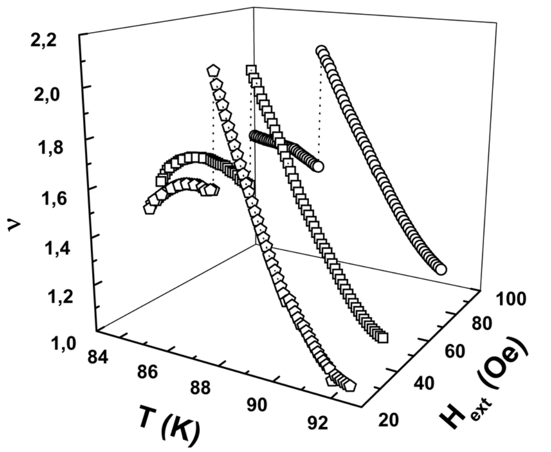

Fig. 7. Temperature dependences of the CVC nonlinearity coefficient ν(T) in Eq. (2). The symbols are the same as in Fig. 5.

phase diagrams in the region of the BKT transitions when external magnetic and electric fields are applied to the object under study. As can be seen, the results of constructing the $T_{\rm BKT}$ – $H_{\rm BKT}$ phase diagram under different external impacts are satisfactorily described by a single relationship (see the dash-dot line in Fig. 8). Possible errors in the determination of TBKT values from the analysis of CVC and the HBKT from the analysis of magnetoresistance isotherms are presented in the figure by horizontal and vertical "whiskers," respectively.

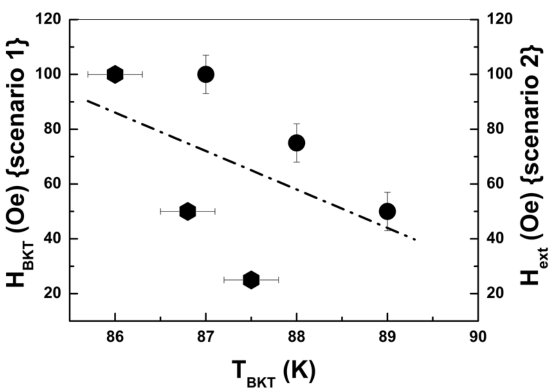

Fig. 8. H-T phase diagram in the region of realization of BKT transitions obtained according to Scenario 1 (circle) and Scenario 2 (hexagon).

5. Conclusion

It was already noted in the Introduction that the aim of this work was to establish the identity of the topological phases arising under two fundamentally different scenarios for the realization of the Berezinskii-Kosterlitz-Thouless topological phase transitions in the Josephson medium of granular HTSCs.

The following was established in the work:

1. It was shown that the two-dimensional Josephson medium of granular HTSCs is the optimal object for studying the BKT phase transitions.

2. It was shown that the criterion for the identity of the topological phases arising during the BKT phase transitions when exposed to an external magnetic field and transport current is the almost complete coincidence of the corresponding H-T phase diagrams.

3. It was established for the first time that the nature of the topological phases arising as a result of the BKT phase transition does not depend on the type of external influence.

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