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Meissner effect and structural inhomogeneity in HTSC $YBa_2Cu_3O_{6.92}$

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For optimally doped high-temperature superconductors $YBa_2Cu_3O_{6.92}$ with various degrees of structural inhomogeneity, the influence of this inhomogeneity on the manifestation of the Meissner effect is considered. The measurement results indicate that for the samples under study, for which almost identical superconducting transition $T_c \sim 92\,K$ temperatures were realized, the Meissner effect values turned out to be different and correlated with the degree of structural inhomogeneity, which is also characteristic of other magnetic properties.

Keywords: Superconductivity, HTSC, structural disorder, magnetic properties, *d*-wave nodes, Fermi arcs, Meissner effect.

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1. Introduction

As it is known, HTSC $YBa_2Cu_3O_y$ are *d*-superconductors. It is also known that an important difference between *s*-wave and *d*-wave superconductivity is that the former is relatively immune to structural disorder, while the latter is — easily destroyed [1,2]. This contributes to a change in the physical properties caused by the presence of structural disordering in the samples $YBa_2Cu_3O_y$. The essence of the difference between *s*- and *d*-superconductors is that the superconducting gap for *s*-superconductors is realized for all directions of the Brillouin zone, while for *d*-superconductors the superconducting gap has nodes in which the gap turns to zero.

In our recent work [3] it was shown that, depending on the degree of structural heterogeneity, the gap near the nodes turns out to be zero not only in the nodes themselves, but also in their vicinity. The more pronounced the structural heterogeneity, the larger areas of the Fermi surface near nodes (nodal points) are not covered by a superconducting gap. In other words, Fermi arcs are formed.

As you know [4], the presence of a superconducting gap is a sufficient condition for the manifestation of the Meissner effect. We believe that the magnitude of this effect should also depend on the sizes of Fermi arcs, which turn out to be different in samples with varying degrees of structural heterogeneity. The present work is devoted to verifying the validity of this statement.

It should be noted that previously the Meissner effect was the subject of a large number of studies, mainly on samples of high chemical and structural quality of single- and polycrystals of HTSC , which minimized the effect of heterogeneity and disorder on magnetization (see, for example, [5–7]).

Particularly, in [5] the Meissner effect was studied on a single crystal $Tl_2Ba_2Ca_2Cu_3O_{10}$. The results obtained confirmed that the observed Meissner effect is an ordinary Ginzburg–Landau superconducting transition in a homogeneous superconductor.

In another work [6], the Meissner effect was systematically studied on a number of single crystals, including $YBa_2Cu_3O_7$. The obtained significant differences in the Meissner fraction fractions were explained on the basis of the vortex pinning model.

In the work [7] it was noted that in polycrystalline HTSC samples, the Meissner and screening effects become incomplete when the crystallite sizes turn out to be commensurate with the penetration depth of the magnetic field (λ).

In this paper, the study is carried out on three polycrystalline samples of the composition $YBa_2Cu_3O_{6.92}$, considered in our previous works, having close values of the temperatures of the superconducting transition T_c from 90.8 K to 91.9 K, but differing in the sizes of crystallites, the degree of controlled structural disordering, and, as it turned out, the sizes of Fermi arcs in the vicinity of *d*-wave nodes [3].

Measurements of the Meissner effect were carried out on a PPMS (Quantum Design) installation.

2. Samples and their physical characteristics

The samples were synthesized using mechanochemistry techniques [8] at different annealing temperatures: $T_{an} = 840$, 900 and 930(°C.)

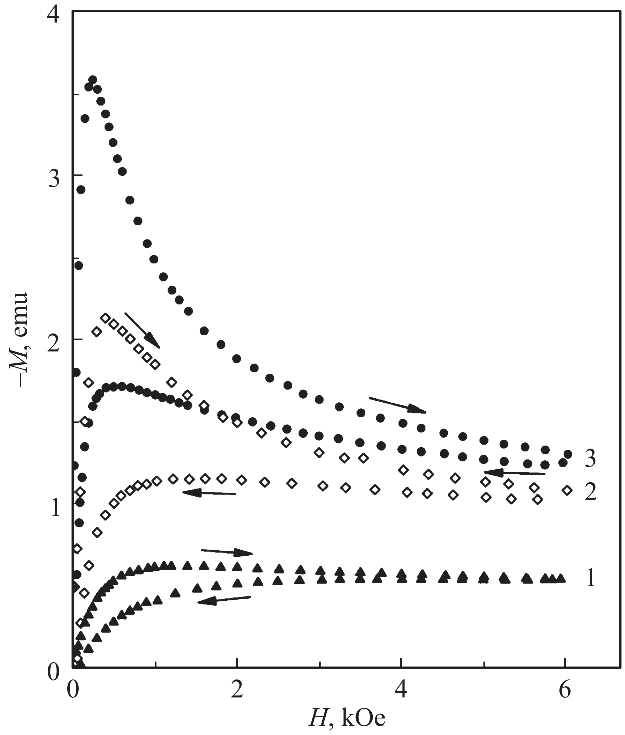

Figure 1. Dependence of the magnetization M on the magnetic field H at $T = 0.9T_c$ for samples $YBa_2Cu_3O_{6.92}$ (according to [9]). (The hysteresis number corresponds to the sample number.)

The lower the annealing temperature was T_{an}, the smaller the crystallite sizes could be realized: $\langle D\rangle = 0.4\,\mu$m (sample № 1), $1\,\mu$m (sample № 2) and $2\,\mu$m (sample № 3). At the same time, the greater the number of defective elementary cells was fixed by the neutron diffraction method [9].

Oxygen saturation of the samples was carried out in the same way. According to the data of iodometric titration, almost identical values of the oxygen index were realized for all three samples ($y = 6.92 \pm 0.03$).

Structural disorder appeared in such samples due to nonequilibrium conditions of synthesis carried out in high-speed mode and at low temperatures.

The obtained values of the average sizes of crystallites turned out to be commensurate with the depth of penetration of the magnetic field λ, and the average size of the area of structural uniformity did not exceed two or three elementary cells [9].

In our work [3], a small review was given containing the results of X-ray data for the samples under consideration, as well as structural characteristics (including the parameters of elementary cells) and magnetic properties, both in variable and permanent magnetic fields.

Magnetic susceptibility in an alternating magnetic field $\chi_{ac}(T)$, demonstrated the realization of superconducting transition temperatures $T_c = 90.8$; 91.2; 91.9 (K) for samples № 1, 2 and 3, respectively. At the same time (according to [9]), the values of the penetration depths of the magnetic field λ for the studied samples № 1, 2 and 3 at a temperature of $T = 0.9T_c$ were different and amounted to the values: 0.485, 0.355 and $0.292\,\mu$m, respectively.

Fig. 1 demonstrates the results of measuring magnetization depending on the magnitude of the applied permanent magnetic field. The average values of magnetization depending on the magnitude of the applied magnetic field obtained during the input and output of the magnetic field are also functions of the penetration depth of the magnetic field λ and the coherence length ξ.

It has been shown that the reason for such a significant difference in the values of λ is a different degree of structural heterogeneity.

In the work [3], special attention was paid to the existence of a temperature-linear contribution to the heat capacity proportional to $\sim (\gamma(0)T)$. Such a contribution to the temperature dependence of the heat capacity is a contribution of a metallic type, which should not be in superconductors with an ideal crystal structure, but at the same time its presence (with different values) is recorded in all works by other authors in which the low-temperature heat capacity of HTSC of this composition was studied (Fig. 2).

As was shown in [3], in structurally heterogeneous HTSC samples, the superconducting gap is suppressed not only at nodal points (as it should be in ideal d-superconductors), but also near nodes. And this effect owes its existence to the depairing mechanism, which is present in the samples due to partial structural disordering. As a result, near the nodes, instead of a linearly vanishing superconducting gap, there is a finite density of states even at 0 K (Fig. 3).

The presence of the contribution $(\gamma(0)T)$ in the expression for the heat capacity for the samples under study was one of the main evidences of the existence of Fermi arcs in the vicinity of d-wave nodes of the superconducting gap, in which superconductivity is completely suppressed. But at

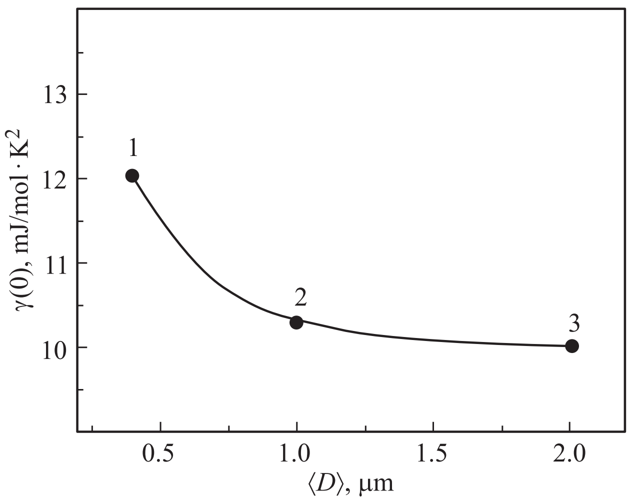

Figure 2. Dependence of the coefficient of the linear temperature contribution to the heat capacity $\gamma(0)$ on the average size of crystallites $\langle D\rangle$. (according to [3]). Digits — sample numbers.

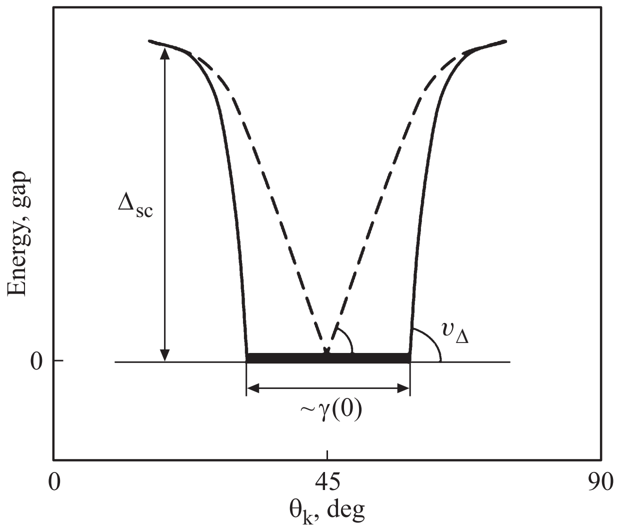

Figure 3. Schematic representation of the region near the d-wave node of a superconducting gap, when superconductivity is completely suppressed not only at the nodal point, but also near it. Dotted line — d-wave node for an ideal superconductor (according to [3]).

the same time, the gap itself is preserved at $T < T_c$ in the other directions of the Brillouin zone (Fig. 2 and 3).

The results obtained in [3] indicate that the Fermi arcs arising in the vicinity of the d-wave nodes for the samples under study have different sizes, the largest of which is realized for the sample № 1, which should mean a real reduction in the size of the superconducting gap for this sample and an increase in the area in which the superconducting gap is completely suppressed.

An interesting question is the influence of the degree of structural heterogeneity on the manifestation of the Meissner effect on the example of the same optimally doped mechanoactivated samples of HTSC № 1, 2 and 3 with different sizes of Fermi arcs near d-wave nodes and, accordingly, with different superconducting gap sizes.

3. Experimental results and discussion

Figure 4 shows the obtained data on measuring the magnetization of the three considered mechanically activated samples of HTSC $YBa_2Cu_3O_{6.92}$, located in the magnetic field $H = 10$ Oe, during their cooling from 100 to 10 K.

It can be seen that when the temperature reaches $T = T_c$, the magnetization of the samples decreases rapidly: the magnetic field lines are pushed out (this is the Meissner effect). It is also seen that the maximum Meissner effect is carried out in the sample № 3, and the minimum — in the sample № 1.

The observed differences in the width of superconducting transitions and, accordingly, in the values of the Meissner effect for the studied samples demonstrate the degree of their structural heterogeneity. With a further decrease in temperature, the magnetization of the samples in the presented scale ceases to change (it reaches a quasi-constant, also different for the samples under study). As shown in Fig. 4, the magnitude of the magnetization turns out to be the smaller (in absolute magnitude), the smaller the crystallite sizes of the sample and the lower the temperature of its synthesis.

We note that it is for the sample № 3, for which the maximum Meissner effect is observed, that the maximum values of magnetization in permanent magnetic fields are also realized (see Fig. 1). At the same time, for the sample № 1, for which the minimal Meissner effect is observed, the crystallite sizes were comparable to the penetration depth of the magnetic field λ. And in this case, as was noted in the work [7], an incomplete Meissner effect should have been expected.

It should also be noted that, namely, for the sample № 3, the maximum jump in heat capacity is observed at the temperature of the superconducting transition T_c [11] and the maximum values of the thermodynamic critical field H_c [10]. It is for this sample № 3 that the minimum values for the contribution to the heat capacity of the metal type $\gamma(0)T$ are realized (see Fig. 2). This corresponds to the minimum value of Fermi arcs in the vicinity of d-wave nodes [3] and means that the superconducting gap has a maximum value in this particular sample № 3.

Let us briefly discuss the reason for the differences noted above in the physical properties of the samples under consideration.

Earlier, for similar samples, neutron diffraction studies of [9] showed that reducing the average size of crystallites to micron and submicron sizes leads to the formation of structural defects of a special type not characteristic of large-crystal samples. In particular, the presence of an antistructural inovalent substitution of Y^{3+} and Ba^{2+} cations was revealed, which is accompanied by changes in the positions of oxygen atoms. It has been shown that such

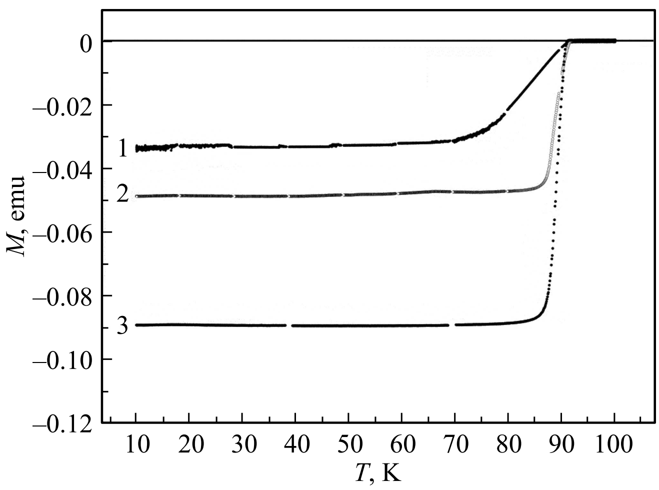

Figure 4. The Meissner effect for the studied samples № 1, 2, 3.

disordering leads to a change in the lattice parameters and their unusual ratio in fine-crystalline samples.

At the same time, in [9], an explanation was also obtained for maintaining high values of T_c in the presence of this type of disordering. It was shown that this type of structural disordering practically does not affect the degree of oxygen filling of the Cu1−O4 chain positions, which determines the level of doping of superconducting planes by charge carriers and, accordingly, the value T_c.

4. Conclusion

Thus, the nanoscale structural heterogeneity realized in fine-crystalline samples, which leads even at optimal values of the oxygen index $y = 6.92$ to changes in fundamental superconducting characteristics (London penetration depth (λ) and coherence length (ξ)), is the reason for the varying degrees of manifestation of the Meissner effect in the studied samples.

The results obtained in this work, indicating the minimal Meissner effect in the sample № 1, are fully consistent with the results of the work [3], in which it was found that for this particular sample a significant proportion of the Fermi surface is uncovered by a superconducting gap.

The correlation of all the results (both those obtained in our previous works and in the present one) clearly indicates that they should be attributed to those natural consequences that are due to different degrees of structural disordering realized during the synthesis of HTSC under different conditions.

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Conflict of interest

The authors declare that they have no conflict of interest.

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