Effect of the Nanoscale Structural Inhomogeneity on the Magnetic and Superconducting Characteristics of Fine-Grained YBa$_2$Cu$_3$O$_y$ HTSCs

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Abstract—It has been experimentally established that the nanoscale structural inhomogeneity, inherent in fine-grained (0.4 ≤ D ≤ 2μm) high-temperature superconductors YBa$_2$Cu$_3$O$_y$ (y = 6.92, $T_C$ = 92 K) and manifesting itself in partial interplane redistribution of oxygen [1, 2], changes the density of states near the Fermi level and decreases the coherence length and density of superconducting carriers in CuO$_2$ planes. The revealed relationship between the changes in these characteristics with respect to their equilibrium values corresponds to the relationship that might occur for conventional superconductors.

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The previous X-ray and Mössbauer data [1–3] suggest that fine-grained high-temperature superconductors (HTSCs) of the YBa$_2$Cu$_3$O$_y$ type are unique objects in which the carrier density in superconducting planes can be changed not only through variation of the total oxygen content but also as a result of partial oxygen redistribution between different layers of the crystal structure. It was of interest to obtain experimental evidences for this suggestion.

The YBa$_2$Cu$_3$O$_y$ ($y = 6.92$, $T_C = 92$ K) samples under study, with micron and submicron average grain sizes, are characterized by a certain type of structural disorder [1, 2] at which, in view of the nonequilibrium synthesis conditions and, in particular, high-speed mechanism of structure formation, only some part of cations occupy equilibrium positions. In some part of unit cells, interchange between Y$^{3+}$ and Ba$^{2+}$ cations occurs, which leads to oxygen redistribution. The oxygen content increases in chain CuO$_2$ planes and decreases in superconducting CuO$_2$ planes. The smaller the average grain size in a sample, the higher the concentration of distorted unit cells and the larger the deviation of the average unit-cell volume $\langle V \rangle$ from its equilibrium value for a given $y$.

It is noteworthy that the scale of change in the volume $V$ is nanoscopic, i.e., smaller than such characteristic parameters as the coherence length $\xi_{coh}(0)$ and the magnetic field penetration depth $\lambda_{pen}(0)$. Hence, the quantity $\langle V \rangle$ acquires a certain physical meaning. Its deviation from the equilibrium value characterizes the degree of structural disorder in the same way as the measured parameter $\delta$ (determination of the latter was described in detail in [1, 2]).

Figure 1 demonstrates the increase in the oxygen $\delta$ amount in chain planes and the decrease in the degree of orthorhombic distortion with a deviation of the average unit-cell volume $\langle V \rangle$ from the optimal value $V_{opt}$, which is characteristic of equilibrium samples with $y = 6.92$. Figure 1 shows also the values of $y$ and $T_C$ for the samples studied; the weak variation in these parameters does not correlate with the changes in $\langle V \rangle$.

Figure 2 shows the experimental dependences of the temperature-independent contribution $\chi_0$ and the coherence length $\xi_{coh}(0)$ obtained for samples of the same series from the analysis of the magnetic susceptibility of the normal state [4] and the magnetization $M$ (measured in the field $H = 6$ kOe at $T = 0.9T_C$) on $\langle V \rangle$.

As was shown in [5, 6], the temperature-independent contribution $\chi_0$ includes several parts: electronic diamagnetism of the atomic core, orbital van Vleck paramagnetism, and spin paramagnetism of conduction electrons. The first two parts are independent of the oxygen content $y$, they are comparable in magnitude but have opposite signs. As a result, they compensate each other to a great extent (with a slightly superior diamagnetic part). In sum, the experimentally observed value $\chi_0$ consists predominantly of the spin (Pauli) susceptibility of conduction electrons, which is determined by the density of states $N(0)$ near the Fermi level: $\chi_0^p \sim N(0)$.

Figure 2a demonstrates an almost linear dependence of the temperature-independent contribution to $\chi_0$ on $\langle V \rangle$ for the samples studied. The value of $\chi_0$ increases with a decrease in $\langle V \rangle$. Previously, a similar change in $\chi_0$ was observed for equilibrium YBa$_2$Cu$_3$O$_y$ samples with an increase in the total oxygen content $y$ [5]. It is known [7] that such an increase in $y$ is accompanied by

a decrease in the unit-cell volume $V$. Figure 2a shows two values of $\chi_0$ corresponding to the data in the literature [5] for the volumes $V$ that are realized in equilibrium samples with $y = 6.92$ and 7. It can be seen that these values of $\chi_0$ fall correlate with high accuracy with the presented linear dependence $\chi_0(V)$, a fact that may indicate its universal character.

The information about the coherence length $\xi_{ab}(0)$ at $T = 0$ K for the samples studied was obtained after subtraction of the background part of the magnetic susceptibility (containing, along with the contribution $\chi_0$, additional contributions caused by the presence of structural defects [8]) from the experimental dependences $\chi_{\text{exp}}(T)$ and comparison of the resulting curve with the formula [9]

$$\frac{\Delta \chi_{ab}}{T} = \frac{A}{\varepsilon} \left[ 1 + \frac{B^2}{\varepsilon} \right]^{-1/2},$$

where $A = 2\mu_0 \pi k_B^2 \xi_{ab}^2(0)/3 \Phi_0 c$, $B = (4\xi_{ab}(0)/\gamma c)^2$, $\xi_{ab}(0)$ is the coherence length in the $ab$ plane at $T = 0$ K, $\gamma$ is the anisotropy parameter, $\Phi_0$ is the magnetic flux quan-