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Temperature Behavior of Conductivity in a $La_2CuO_{4+\delta}$ Single Crystal upon the Paramagnetic–Antiferromagnetic Transition

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Abstract—The temperature dependence of the resistance of a $La_2CuO_{4+\delta}$ ($\delta \approx 0.05$) single crystal with the Neel temperature $T_N \approx 205$ K was investigated in order to establish the correlation between the transport and magnetic properties of the crystal. The $R(T)$ dependence near T_N reveals a kink related to the enhancement of sample's conductivity upon the transition from the antiferromagnetic to paramagnetic state. With an increase in temperature far above T_N, the transition from the dielectric ($dR/dT < 0$) to metal ($dR/dT > 0$) occurs. The observed behavior of resistance is attributed to delocalization of carriers above T_N.

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INTRODUCTION

The study of cuprate superconductors is a fundamental problem of physics of condensed matter. The nature of superconductivity in these compounds, discovered more than twenty years ago, remains understudied. It is clear, however, that their magnetic and superconducting properties are closely interrelated. In the normal state, the conducting properties can also depend on the magnetic state of the system. In a La_2CuO_4 single crystal, e.g., the metamagnetic transition from the antiferromagnetic (AFM) to weak ferromagnetic state results in a sharp rise in conductivity [1, 2]. Studying the interaction between charge carriers and a magnetic subsystem is important not only for high-temperature superconductors, but for a wide class of magnetic conductors and semiconductors in general.

The aim of this work was to establish a possible correlation between the transport and magnetic properties of a $La_2CuO_{4+\delta}$ single crystal. Undoped La_2CuO_4 is an AFM insulator with $T_N \approx 320$ K [3]. Doping of the crystal with excess oxygen ($\delta \neq 0$) leads to the occurrence of charge carriers (holes) and suppresses the AFM order (i. e., it lowers T_N). These properties of the La_2CuO_4 single crystal are determined to a great extent by its crystal and magnetic structures [3, 4]. Within the investigated temperature range (below 430 K), La_2CuO_4 has an orthorhombic perovskite-like lattice consisting of alternating CuO_2 and La_2O_2 layers. In the *Bmab* space group, the CuO_2 layers are perpendicular to the *c* axis and parallel to the (*ab*) plane [3]. It is assumed that the charge carriers (holes) are mainly of the oxygen type. Nonstoichiometric oxygen ($\delta \neq 0$) is localized in the $La_2O_{2+\delta}$ layers between the neighboring CuO_2 planes [5]. This ensures delocalization of holes from the CuO_2 planes and yields 3D conductivity. The magnetic structure is formed by copper ions d^9Cu^{2+} with spin $S = 0.5$. Spins at the neighboring Cu^{2+} sites are oppositely directed and parallel to the orthorhombic *b* axis. Each CuO_2 layer has a weak ferromagnetic moment perpendicular to this layer. Below T_N, the magnetic moments in the neighboring CuO_2 planes are oppositely directed, so the entire system behaves as a 3D AFM [1].

As is well known, the transition from the paramagnetic (PM) to AFM state in metal conductors is usually accompanied by a decrease in the magnetic term of resistivity, which causes a kink in the $R(T)$ dependence [6], or even a noticeable jump in resistivity upon the transition to the AFM state [7]. In magnetic conductors, the effect of spin ordering on resistivity at $T \leq T_N$ is still understudied. It is known, however [8, 9], that conductivity in these systems has a minor $R(T)$ kink at $T \approx T_N$. We might expect that such an effect would also be observed in conductivity of $La_2CuO_{4+\delta}$.

It should be noted that the effect of the PM–AFM transition on the temperature dependence of resistivity was studied earlier for some underdoped cuprate superconductors. For a $YBa_2Cu_3O_{6+\delta}$ single crystal, the temperature dependence of resistivity when current is perpendicular to the base plane has a pronounced feature near T_N, and when the current is directed parallel to the CuO_2 layers, resistivity has no features at $T = T_N$ [10]. Similar behavior has been observed for underoped $La_{2-x}Sr_xCuO_4$ [11]. In both cases, the strong anisotropy of the quasi-two-dimensional (2D) conductivity of these layered compounds was revealed. An analysis of the available literature data shows that there is no clear answer to the question about the presence of an anomaly in the transport properties near the AFM transition in cuprates. Some fundamental questions concerning this effect remain

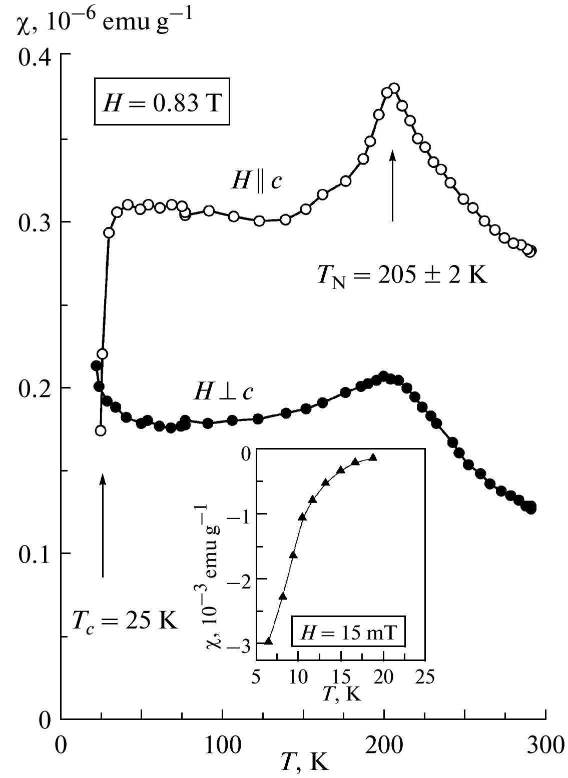

Fig. 1. Temperature dependence of magnetic susceptibility. The insert shows the diamagnetic response in the superconducting state.

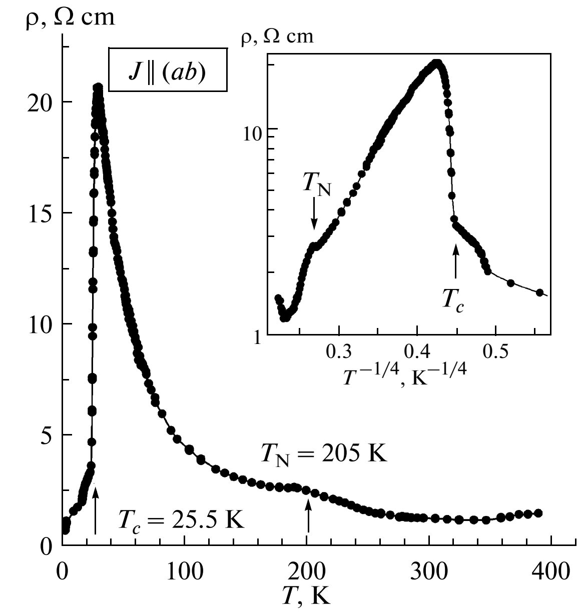

Fig. 2. Temperature dependence of resistivity in the (*ab*) plane.

unanswered. For instance, in the cases when there is the anomaly near T_N, it is important to know how universal it is and which factors are responsible for it. We believe that the results of our study will help answer these questions.

EXPERIMENTAL

We used a sample of the $La_2CuO_{4+\delta}$ single crystal $1.5 \times 2 \times 2$ mm^3 in size. This sample was studied earlier in [12]. In that work, the value $\delta \approx 0.05$ is estimated and showed that the sample must be inhomogeneous and consist of a mixture of the AFM and superconducting phases. Indeed, the temperature dependence of magnetic susceptibility $\chi(T)$ measured in this work (Fig. 1) exhibited both AFM (T_N = 205 ± 2 K) and superconducting ($T_c \approx 25$ K) transitions, reflecting the state of phase separation. The obtained values T_N and T_c are in good agreement with the values reported in [12].

RESULTS AND DISCUSSION

The temperature dependence of resistivity $\rho(T)$ was determined using the four-probe method in a zero magnetic field ($H = 0$) at current $J \le 100$ μA. The current passed both along and across the CuO_2 planes. The current value was chosen from the measured CVCs such that Ohm's law was obeyed over the entire measuring temperature range. The temperature behavior of the $\rho(T)$ dependence recorded for the current directed along the CuO_2 planes (Fig. 2) was absolutely consistent with χ(T), indicating a resistive superconducting transition at $T_c \approx 25.5$ K and the pronounced feature (kink) near $T_N \approx 205$ K.

Despite the occurrence of the superconducting transition, the variable-range hopping conductivity $[\ln\rho(T)] \propto T^{-1/4}$ [13] was also revealed in this sample at temperatures between T_c and T_N (Fig. 2). It can be seen that T_N resistivity decreases faster with increasing temperature. In addition, at $T_{min} \approx 350$ K corresponding to the minimum resistivity, we observe a transition from the nonmetal $R(T)$ dependence ($d\rho/dT < 0$) to the metal dependence ($d\rho/dT > 0$). The superconducting resistive transition with current directed in the CuO_2 plane is quite sharp (Fig. 2). The temperature $T_c \approx 25.5$ K is determined as the $R(T)$ curve inflection found by variations in the dR/dT derivative. In the low-temperature region of the resistive transition (at $T \le 25.5$ K), we can see the pronounced shoulder in the $\rho(T)$ curve that is usually observed in granular high- and low-temperature superconductors with fairly weak intergrain bonds [14, 15]. We might suggest that the superconducting areas in this inhomogeneous sample form a sufficiently long chain that yields the sharp resistive superconducting transition. However, some bonds in this chain appear weak; they determine the shoulder in the low-temperature region in the resistive transition curve [14, 15].

In the direction perpendicular to the (*ab*) plane ($J \| c$), resistivity is much higher than that for the current directed along the (*ab*) planes (Fig. 3). Neverthe-

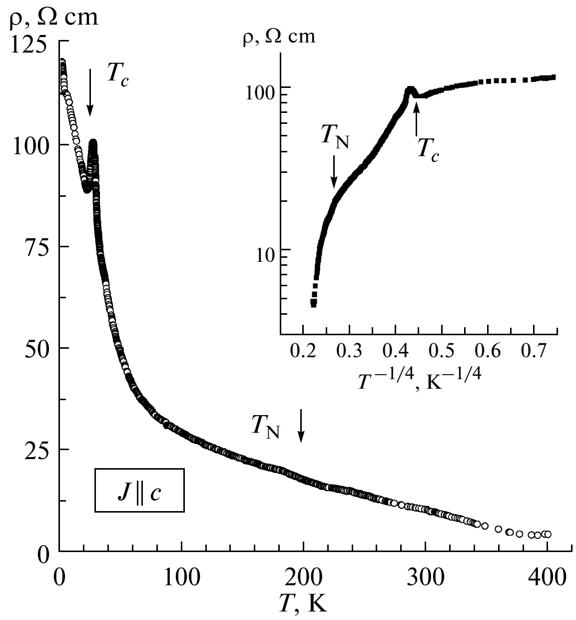

Fig. 3. Temperature dependence of resistivity in the direction perpendicular to the (*ab*) plane.

less, in this case, the temperature dependence of resistivity also has features similar to those observed for the current directed in the plane. Superconductivity manifests itself as a noticeable drop in resistivity when approaching the transition temperature $T_c \approx 25.5$ K from the direction of higher temperatures. Resistivity does not drop to zero, however, indicating higher phase inhomogeneity in this direction. As a result, no continuous superconducting channel forms. The variation in the $\rho(T)$ behavior after the temperature rises above T_N is identical to the behavior when the current is directed along the CuO_2 planes. There is also a transition from the nonmetal to metal $\rho(T)$ behavior: the resistivity minimum is observed at $T_{min} \approx 385$ K.

CONCLUSIONS

Our results clearly demonstrate the correlation between the magnetic and conducting properties of underdoped $La_2CuO_{4+\delta}$. Above T_N, the system becomes less resistive and more metallic; upon further increase in temperature, far above T_N, the nonmetal–metal transition occurs. This is consistent with the known theoretical concepts and some experiments [16]. According to these concepts, the AFM order enhances the localization of holes, while thermal excitations break the AFM order and lead to the delocalization of carriers, so that above T_N with increasing temperature the system can approach the metal state. At temperatures $T \approx T_N$, only the interplanar AFM order vanishes, while the AFM order inside the CuO_2 planes remains even at temperatures far above T_N. At the same time, the length of the AFM correlations ζ_{AF} declines strongly with increasing temperature above T_N [3], which should be accompanied by an increase in the mobility of holes [17]. A strong increase in conductivity above T_N can in some cases lead to the nonmetal–metal transition observed in our studies. These effects are revealed in conductivity both in the CuO_2 plane and in the direction perpendicular to these planes, due to the 3D character of hopping conductivity in $La_2CuO_{4+\delta}$.

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