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INFLUENCE OF MAGNETIC FIELD ON THE SUPERCONDUCTING TRANSITION IN A $Nd_{1.82}Ce_{0.18}CuO_{4-\delta}$ FILM

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The temperature and magnetic-field dependences of the resistivity ρ and Hall effect R ($\mathbf{j}||ab, \mathbf{B}||c$) in a $Nd_{1.82}Ce_{0.18}CuO_{4-\delta}$ single crystal film ($T_c = 6$ K) is investigated at temperatures $1.4 \leq T \leq 20$ K and magnetic fields $0 \leq B \leq 5.5$ T. At the lowest temperature $T = 1.4$ K the resistive state (exhibiting resistivity and Hall effect) arises in a magnetic field $B = 0.5$ T. A transition to the normal state is completed at $B_{c2} \simeq 3$ T, where the Hall coefficient becomes nearly constant. The negative magnetoresistance due to the weak-localization effect in the normal state is observed for $B > 3$ T. The nonmonotonic behavior and the inversion of the sign of $R(B)$ in the mixed state are explained in a reasonable way by the flux-flow model with the effect of pinning taken into account.

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The crystallographic structure of $Nd_{2-x}Ce_xCuO_{4-\delta}$ is the simplest among the superconducting (SC) cuprates: each copper atom is coordinated to four oxygen atoms in a simple planar structure without apical oxygen. The single crystal can therefore be regarded as an analog of a two dimensional (2D) system (a collection of 2D conducting planes separated from each other by a distance $d \simeq 6$ Å). In accordance with a such a structure, $Nd_{2-x}Ce_xCuO_{4-\delta}$ single crystals have a high anisotropy factor of the resistivity in the normal phase, $\rho_c/\rho_{ab} \simeq 10^4$ [1, 2].

The vanishing of superconductivity in $Nd_{2-x}Ce_xCuO_{4-\delta}$ single crystals or films is accompanied by the onset of 2D weak-localization effects. Thus a linear dependence of ρ on $\ln T$ comes about for samples with $x \simeq 0.15$, in which the superconducting state is completely destroyed by a magnetic field [3, 4]. Furthermore, a highly anisotropic negative magnetoresistance (NM), predicted for 2D weak localization, was observed in the nonsuperconducting state at low temperature (samples with $x < 0.11$ [5] and unreduced samples with $x = 0.15$ [6]).

The flux separation technique has been used previously for deposition of NdCeCuO thin films [7].

In this paper we report the results of an experimental study of the resistance ρ and Hall effect R ($\mathbf{j}||ab, \mathbf{B}||c$) of a $Nd_{1.82}Ce_{0.18}CuO_{4-\delta}$ single-crystal film in the temperature range $T_c \leq T \leq 300$ K in zero magnetic field and at temperatures $1.4 \leq T \leq 20$ K in magnetic fields up to $B = 5.5$ T. The resistivity ρ_{ab} of the $Nd_{1.82}Ce_{0.18}CuO_{4-\delta}$ thin film (~ 5000 Å) was measured by the four-terminal method to be 0.22 mΩ·cm at $T = 300$ K and $\rho = 0.06$ mΩ·cm at $T = 8$ K. In the

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temperature range $20 \leq T \leq 180$ K the behavior of the resistivity is described by the law $\rho = \rho_0 + AT^2$, where $\rho_0 = 6.42 \cdot 10^{-5}$ Ω·cm, $A = 2.25 \cdot 10^{-9}$ Ω·cm/K^2.

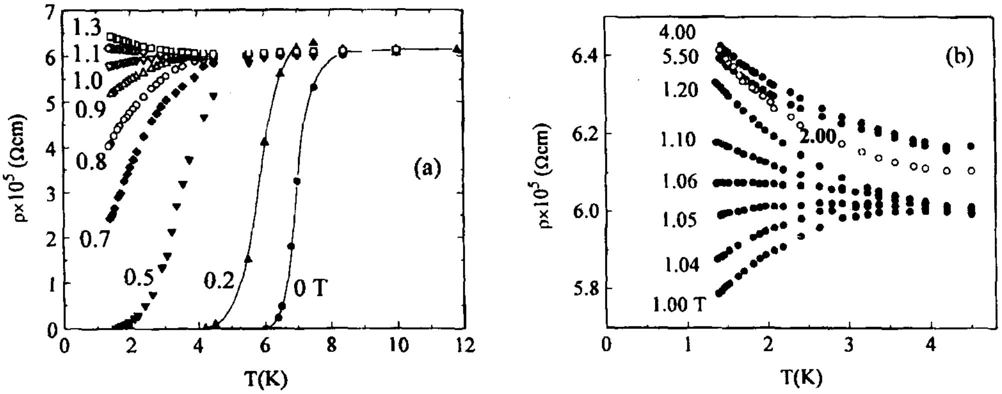

Fig.1. *a* – Temperature dependence of the resistivity in different magnetic fields. *b* – Temperature dependence of the resistivity for several different fields up to $B = 5.5$ T

Figure 1 shows the temperature dependence of the resistivity of the sample in different magnetic fields. The SC transition temperature is $T_c = 6$ K at $B = 0$ and it shifts to lower temperatures as the field increases. In fields $B > 0.5$ T the superconducting transition begins to broaden: the positive temperature coefficient $d\rho/dT$ of the isomagnetic curves decreases with increase of B. In the field $B = 1.06$ T the coefficient $d\rho/dT$ changes sign and remains negative up to $B = 5.5$ T for $T \leq 5$ K (see Fig. 1*b*).

The positive Hall effect appears in the same fields as does the resistivity: $B = 0.5$ T at $T = 1.4$ K and $B = 0.2$ T at $T = 4.2$ K (Fig. 2*a*, *b*). An abrupt change in sign of the Hall coefficient R from positive to negative is observed in fields $B \simeq 1.5$–2 T, and the value R is nearly constant at $B \geq 3$ T : $R = 5.5 \cdot 10^{-4}$ cm^3/C. This value of R correlates with the value of R in the normal state at $T > T_c$ and corresponds to an electron density $n \simeq 1.1 \cdot 10^{22}$ cm^{-3}.

The value obtained for the first critical field from magnetic investigations of $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ ceramics is $B_{c1} = 8 \cdot 10^{-2}$ T [8]. Evidently the value of B_{c1} for single crystals is of the same order of magnitude. Nevertheless, the sample remained in the superconducting state in a finite temperature interval up to $B \simeq 0.5$ T (see Fig. 1*a*). This is a consequence of vortex lattice pinning owing to any spatial inhomogenity of material. The enhancement of the Lorentz force with increasing magnetic field leads to a transition to the resistive state at $B \simeq 0.5$ T for the lowest temperature $T = 1.4$ K and at $B \simeq 0.2$ T for $T = 4.2$ K (see Fig. 2*a*).

When the pinning is included in the flux-flow model the resistivity ρ_f for a sample in the mixed state is given by [9, 10]

$$\rho_f(B) = \rho_n \frac{B - B_p}{B_{c2}}. \tag{1}$$

Here ρ_n is the normal-state resistivity, B_{c2} is the second critical field, and B_p is the depinning field ($B_p = F_p/j$, where F_p is the pinning force density and j is the current density).

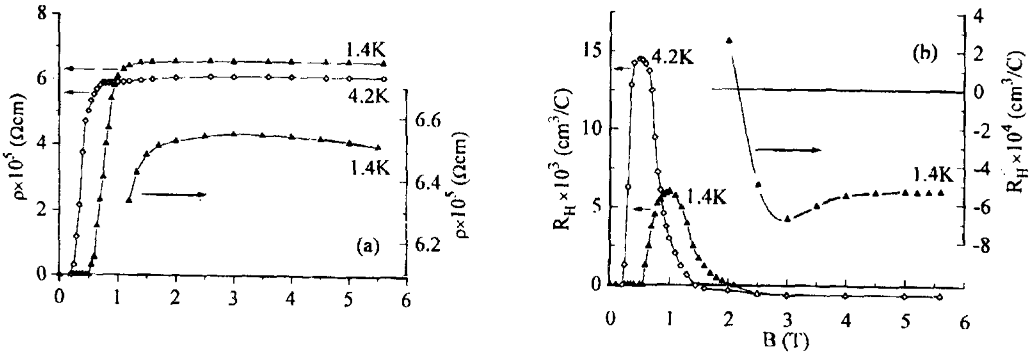

Fig.2. *a* The resistivity as a function of magnetic field at $T = 1.4$ K and 4.2 K. *b* The Hall coefficient as a function of magnetic field at $T = 1.4$ K and 4.2 K

The transition to the normal state is completed at $B \geq 3$ T, when the Hall coefficient becomes nearly constant. It should be noted that weak negative magnetoresistance $d\rho/dB < 0$ appears at $B > 3$ T as well (see Fig. 2*a*). According to Eq. (1) the derivative $d\rho_f/dB$ is positive in the mixed state at $B < B_{c2}$. Thus the observed NM must be the consequence of magnetic-field dependence of the normal-state resistivity $\rho_n(B)$. One can therefore consider $B_{c2} \simeq 3$ T to be the second critical field.

To find the coherence length ξ_0 it is necessary to define the mean free path $\bar{\ell}$. Using the experimental value $\rho = 0.06$ mΩ·cm, we obtain the value $R_\Box \simeq 10^3 \Omega$ for the surface resistance of a CuO_2 layer. Setting $\sigma_\Box^{-1} = R_\Box$ in the relation [11]

$$\sigma_\Box = (e^2/h) k_F \bar{\ell}, \tag{2}$$

we estimate $k_F\bar{\ell}=25$ and $\bar{\ell} \simeq 4 \cdot 10^{-7}$ cm, since $k_F \simeq 6 \cdot 10^7$ cm^{-1}. Using the formula [12]

$$B_{c2} \simeq c\hbar / e\xi_0 \bar{\ell}, \tag{3}$$

which is correct for $\xi_0 \gg \bar{\ell}$, we find the coherence length in the *ab* plane to be $\xi_0 = 5 \cdot 10^{-6}$ cm, which is in fact much more than $\bar{\ell}$.

In fields $B > 3$ T the $\rho(T)$ curves at temperatures $1.4\ K \leq T \leq 4.5$ K are described well by the function

$$\rho = -\rho_0 \cdot \ln(T/T_0) \tag{4}$$

(see Fig. 3). The logarithmic dependence of the resistivity is characteristic of a 2D electron gas in the low-temperature region, where quantum corrections owing to localization effects or electron–electron interaction are important. Those corrections to the metallic conductivity are of order $(k_F\bar{\ell})^{-1}$ and decrease with magnetic field. This is the cause of the negative magnetoresistance. The observed NM effects are rather small but persist up to the highest fields. They are more likely to be electron–electron interaction corrections than localization effects. Figure 3 also shows the experimental points for $B = 1.5$ T. The discrepancy between the experimental points and the logarithmic law indicates that the normal state has not yet been attained at $B = 1.5$ T.

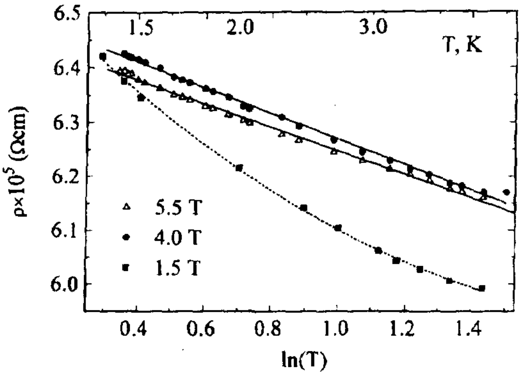

Fig.3. Resistivity of the sample as a function of the logarithm of the temperature at three different magnetic fields

Thus we arrive at the conclusion that the low-temperature behavior of the resistivity of the superconducting $Nd_{1.82}Ce_{0.18}CuO_{4-\delta}$ single-crystal film in the normal state at $B > B_{c2} \simeq 3$ T is due to quantum corrections to the conductivity of a 2D electron gas. The change in sign of the temperature coefficient $d\rho/dT$ in the resistive state occurs at a certain magnetic field $B \simeq 1.06$ T. This sign change is not connected with any phase transition (for example, a transition to a vortex glass phase, as in Fisher's theory [13]) but corresponds to an accidental compensation of two factors in Eq. (1): a decrease of B_{c2} with temperature, and a negative value of $d\rho/dT$ in the normal state owing to the weak-localization effect.

The onset of the Hall resistivity occurs at the same field (0.5 T at 1.4 K) as does the onset of the magnetoresistivity. In the usual flux-flow model the Hall effect in the mixed state arises because of the hydrodynamic forces acting on moving vortices and in the absence of pinning should have the same sign as that in the normal state [14, 15]. In the treatment of Jia et al. [10], which includes the back-flow current due to pinning forces, the Hall resistivity for a mixed state in the approximation of Bardeen and Stephen is given by

$$\rho^f_{xy}(B) = \rho_f(B)\mu B_{c2}\left[\frac{B}{B_{c2}} - \frac{2B_p}{B}\right] \tag{5}$$

where μ is the charge carrier mobility. Equation (5) predicts that at low fields the pinning term B_p/B will dominate over Lorentz term B/B_{c2}, so that the Hall effect will have a sign opposite to that in the normal state. From Eqs. (1) and (5) we have for Hall coefficient $R = \rho_{xy}/B$ in the flux-flow regime

$$R_f(B) = R_n\frac{(B - B_p)}{B}\left[\frac{B}{B_{c2}} - \frac{2B_p}{B}\right], \tag{6}$$

where $R_n = \rho_n\mu$ is the Hall coefficient in the normal state. According to Eq. (6) the inversion of the sign of $R_f(B)$ should take place at a field

$$B_{\rm inv} = \sqrt{2B_pB_{c2}} \tag{7}$$

and for $B < B_{inv}$ the value of $R_f(B)$ should attain a maximum at

$$B_{\max} \simeq 2B_p. \tag{8}$$

The observed behavior of $R(B)$ can be interpreted on the basis of the flux-flow model. In the investigated $Nd_{1.82}Ce_{0.18}CuO_{4-\delta}$ film the Hall coefficient in the normal state is negative ($R_n < 0$), and so R_f should be positive for $B < B_{inv}$. Relation (8) actually does hold: $B_p = 0.5$ T, $B_{max} \simeq 1$ T for 1.4 K and $B_p = 0.2$ T, $B_{max} \simeq 0.4$ T for $T = 4.2$ K (see Fig. 2*b*). Equation (7) may be used for a rough estimate of the second critical field. We have $B_{inv} = 2.2$ T and 1.4 T for $T = 1.4$ K and $T = 4.2$ K, respectively, and then $B_{c2} \simeq 5$ T, in reasonable agreement with our previous estimate.

It should be noted that attempts to explain the behavior of $R(B,T)$ by a two-band model with high-mobility holes and low-mobility electrons [1] meet with too many contradictions. In particular, it is very difficult to obtain the essential temperature dependence of B_{inv}. In the flux-flow model the observed behavior of $B_{inv}(T)$ is a natural consequence of the decrease of both B_p and B_{c2} with increasing T (see Eq. (7)).

In summary, we have investigated the magnetic field influence on the resistivity and Hall effect of a superconducting $Nd_{1.82}Ce_{0.18}CuO_{4-\delta}$ film at low temperatures. The observed behavior of the resistivity as a function of the magnetic field and temperature may be described by a combination of the flux-flow regime at $B < B_{c2}$ and the 2D weak-localization regime at $B > B_{c2}$. The Hall coefficient dependences on B and T may be also reasonably explained in the framework of flux-flow model with the inclusion of the back-flow of vortices owing to the pinning forces.

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