Destruction of superconductivity in a $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ single crystal by a magnetic field: 2D character of the transition

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An investigation of the effect of a magnetic field (**B**||**c**) on the behavior of the resistance of a $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ single crystal ($T_c = 14$ K) showed that the transition into the normal phase can be interpreted on the basis of the theory of dynamic scaling for the conductivity of disordered two-dimensional (2D) systems. The temperature dependence $R \sim \ln T$ of the normal-phase resistance at temperatures $T \leqslant 10$ K corresponds to weak localization in the 2D system. © *1995 American Institute of Physics.*

In the present paper we report the results of an experimental study of the resistance of a bulk $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ single crystal in the temperature range $T_c \leqslant T \leqslant 300$ K without a magnetic field and in the temperature range 1.3 K $\leqslant T \leqslant 25$ K in a magnetic field $0 < B \leqslant 10$ T . The dimensions of the experimental single crystal were $2.5 \times 1.7 \times 0.05$ mm. An x-ray crystallographic analysis of the structural state showed that the experimental sample is a good single crystal. This is indicated by the character of the back-reflection pattern: The system of interference maxima belongs to one crystallographic orientation and there are no Debye rings in the x-ray diffraction patterns. The superconducting transition temperature of the single crystal is $T_c = 14$ K, and the width of the complete transition is $\Delta T \cong 2$ K. The anisotropy of the electrical resistance was measured by a modified Montgomery method.[1] The temperature was monitored with a germanium temperature sensor and a copper-constantan thermocouple. The resistivity of the sample at $T = 300$ K is $\rho_{ab} = 0.165$ m$\Omega \cdot$cm and $\rho_c = 2.3$ $\Omega \cdot$cm. The anisotropy factor is $\rho_c / \rho_{ab} = 1.4 \times 10^4$ at $T = 300$ K, which is less than for the best BiSrCaCuO crystals (10^5), but much higher than for YBaCuO (10^2). In Ref. 2 the same value $\rho_c / \rho_{ab} \cong 10^4$ was reported for NdCeCuO single crystals. In Ref. 3 we give a detailed discussion of the anisotropy and temperature dependence of the resistivity and thermal emf.

The temperature dependences of the resistivity of a $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ single crystal in different magnetic fields (**B**||**c**) in the temperature range 1.3 K $< T < 25$ K are shown in Fig. 1. In fields $B < 3$ T the superconducting transition shifts parallel to itself into the range of lower temperatures (Fig. 1a). The superconducting transition begins to broaden in the field $B = 4.5$ T. As the field increases, the positive temperature coefficient

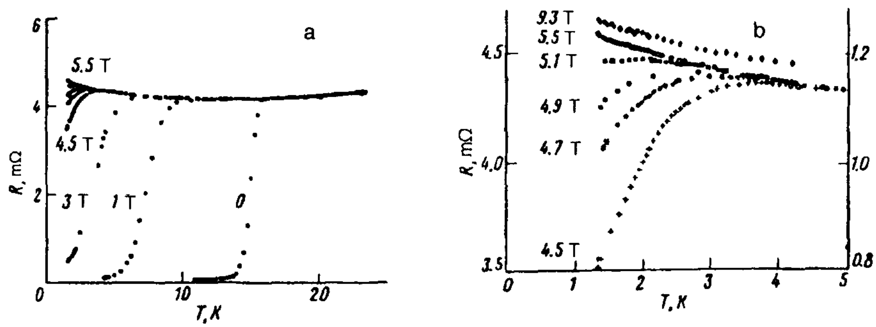

FIG. 1. Temperature dependence of the resistance (j||ab) in a static magnetic field (B||c) for a $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ sample ($R_{\square}$—surface resistance of a CuO_2 layer). For clarity, the curve $R(T)$ at 9.3 T is shifted upward by 0.05 mΩ.

dR/dT of the isomagnetic curves decreases in the transition region (Fig. 1b), and in the field $B=5.5$ T the resistivity increases as the temperature decreases ($dR/dT<0$). In the field $B=5.5$ T the temperature dependence $R(T)$ at temperatures $T\leqslant 10$ K is described well by the function $R(T)=-R_0 \ln T/T_0$ (Fig. 2). Further increase of the magnetic field to $B\cong 10$ T does not change the temperature dependence of the resistivity.

It is well known that $Nd_{2-x}Ce_xCuO_{4-\delta}$ has a special place among the oxide superconductors with the perovskite structure. The standard high-T_c oxide superconductors contain CuO_2 layers with pyramids or octahedra, while the system $Nd_{2-x}Ce_xCuO_{4-\delta}$ consists of CuO_2 layers with no apical oxygen atoms; i.e., the CuO_2 layers form ideal two-dimensional planes. Therefore, the $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ single crystal can in some sense be regarded as an analog of a two-dimensional (2D) system (collection of 2D conducting planes). There is no doubt that the observed anisotropy of the

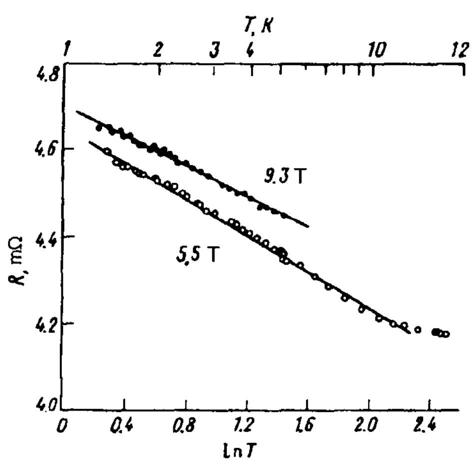

FIG. 2. Resistance of the sample as a function of the logarithm of the temperature in different magnetic fields. The curve $R(\ln T)$ at 9.3 T is shifted upward by 0.05 mΩ.

resistivity $\rho_c/\rho_{ab} \cong 10^4$ is associated with this circumstance. For nonoptimal doping of the system $Nd_{2-x}Ce_xCuO_{4-\delta}$ ($x=0.15; \delta=0.04$) a natural disorder appears in the distribution of both the cerium cations and the oxygen anions. This disorder can be described by a random impurity potential. It is natural, therefore, to use the scaling theory for the conductivity of disordered 2D systems to analyze the curves $R(B,T)$ obtained by us.[4]

We shall study the magnetic-field-induced phase transition (with a constant disorder) on the basis of the theory of critical phenomena. Let B_c be the critical magnetic field of the transition. The characteristic length ξ of the system (the coherence length of the wave functions of the cooper pairs) in magnetic fields B close to B_c will then diverge according to a power law

$$\xi \sim |B-B_c|^{-\nu}, \tag{1}$$

where $\nu > 0$ is the static critical exponent. At the same time, the characteristic frequency Ω of the system near the transition is related to ξ by the relation

$$\Omega \sim \xi^{-z}, \tag{2}$$

where z is the dynamic critical exponent. In the case of a superconducting system the quantity $\Omega = \Delta_c/\hbar$, where Δ_c is the superconducting gap, plays the role of the characteristic frequency. It follows from Eqs. (1) and (2) that as $B \rightarrow B_c$, the superconducting gap approaches zero in the following way:

$$\Delta_c \sim \xi^{-z} \sim |B-B_c|^{z\nu}. \tag{3}$$

For a 2D system the surface resistance $R_\square$ is a scale-invariant quantity. This means that near the transition the quantity $R_\square$ can depend on the temperature only via the ratio $k_B T/\Delta_c$. Using relation (3), we find that as $B \rightarrow B_c$

$$R_\square = R_\square^c f(a(B-B_c)/T^{1/z\nu}), \tag{4}$$

where f is a dimensionless analytic function (scaling function), and a is a constant. From Eq. (4) we have

$$(dR_\square/dB)|_{B=B_c} = R_\square^c f'(0) a T^{-1/z\nu}, \tag{5}$$

where $f'(0) = (df/dB)|_{B=B_c}$. Scaling theory for 2D systems predicts the critical exponents $z=1$ and $\nu \geqslant 2/d = 1$ (d is the dimension of the system).

Defining the critical transition field B_c as the field in which the temperature coefficient of the resistance changes sign $(dR/dT)|_{B=B_c}=0$, we obtained for the experimental sample $B_c = 5.20 \pm 0.05$ T at the minimum experimental temperature $T = 1.3$ K (Fig. 3). Using for the field B_c that destroys superconductivity in a two-dimensional system a relation similar to the Ginzburg–Landau relation for the second critical field

$$B_c \xi_0^2 = \Phi_0/2\pi, \tag{6}$$

where ξ_0 is the coherence length in the **ab** plane with $B=0$ and $\Phi_0 = \cosh/2e$ is the magnetic flux quantum, we can estimate the quantity ξ_0. For our experimental crystal with $B_c = 5.2$ T the coherence length in the CuO_2 plane is ≈ 80 Å .

The surface resistance $R_\square$ of a CuO_2 layer is determined by the relation $R_\square = RS/(ld)$, where S is the cross section of the sample, l is the distance between the

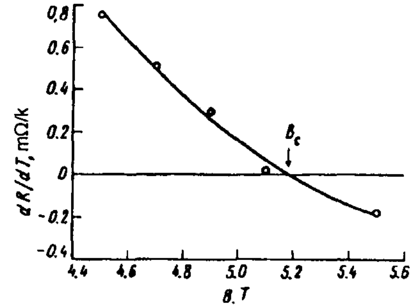

FIG. 3. dR/dT as a function of the magnetic field at the temperature $T=1.3$ K.

contacts, and $d=6.03$ Å is the distance between the CuO_2 layers in the $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ single crystal. The critical value of the surface resistance, which corresponds to the resistance $R_\square$ with $B=B_c$, was found to be $R_\square^c=1.2$ kΩ.

The curve $\log(dR/dB)|_{B=B_c}$ versus $\log(1/T)$ is shown in the inset in Fig. 4. We see that in the temperature interval 1.3 K $<T<$ 3 K and in the experimental range of magnetic fields the points fall on a straight line in accordance with the expression (5). From the slope of the curve $\log(dR/dB)|_{B=B_c}$ versus $\log(1/T)$, according to Eq. (5), we determined the product of the dynamic and static critical exponents $z\nu=1.1\pm0.1$. If B_c and the product $z\nu$ are known, the scaling relation (4) can be checked directly. In Fig. 4 the function $R(B,T)$ for the experimental sample is shown as a function of the parameter $|B-B_c|/T^{1/z\nu}$. We see that the experimental data conform well to the two universal scaling curves for $B<B_c$ and $B>B_c$.

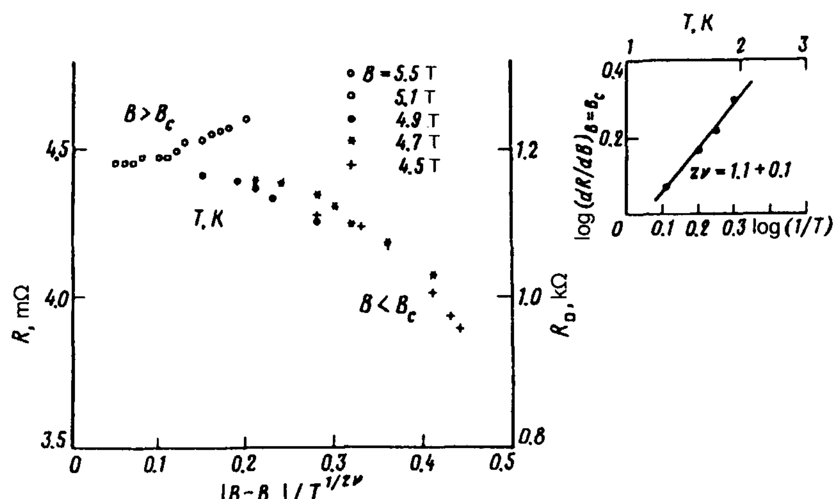

FIG. 4. Resistance R as a function of the scaling variable $|B-B_c|/T^{1/z\nu}$. $B_c=5.25$ T, $z\nu=1.1$.

Thus analysis shows that in the critical field B_c we have a continuous phase transition which is described by a scaling relation, but the question of the microscopic nature of this transition remains open. Studying the quantum fluctuations of the phase of the order parameter in a disordered 2D system, Fisher[4] showed that a magnetic-field-induced superconductor–insulator transition can occur at $T=0$. According to Ref. 4 , a transition occurs from the vortex-glass phase with localized Abrikosov vortices and delocalized pairs (superconductor) into an electronic-glass phase with delocalized vortices and Cooper pairs, which are localized on the fluctuations of a random potential (insulator). At the transition point $B=B_c$ both vortices and pairs are delocalized; this corresponds to a Bose metal with a universal value of the critical resistance $R_{\square}^c$, which is close to the resistance quantum for a Cooper pair $h/(2e)^2=6.45\ \mathrm{k}\Omega$. The superconductor–insulator transition observed in α-InO_x films ($R_{\square}^c=4.45\ \mathrm{k}\Omega$)[5] and in $Nd_{2-x}Ce_x$ CuO_4 films ($R_{\square}^c=8.50\ \mathrm{k}\Omega$)[6] was interpreted by the authors on the basis of these ideas.

In studying the effect of a magnetic field on the superconducting transition in α-MoGe films, Yazdani and Kapitulnik[7] called attention to the nonuniversality of the value of $R_{\square}^c$ for the experimental samples. Their values of $R_{\square}^c$ are much (3–10 times) smaller than $h/4e^2$ and are close to the critical field B_c of the phase transition, irrespective of the values obtained for the second critical field B_{c2}. The authors attribute the low values of $R_{\square}^c$ in their samples to the contribution of unpaired electrons to the conductivity—this contribution is large for $T \neq 0$ in fields B close to B_{c2}—while maintaining at the same time Fisher's representation[4] for a transition of a superconductor at $B=B_c$ into the insulating phase with localized Cooper pairs.

Our value $R_{\square}^c=1.2\ \mathrm{k}\Omega$ is also much (5 times) smaller than the value predicted by Fisher's theory. The determination of the second critical field (for $\mathbf{B}\|\mathbf{c}$) by extrapolation of the values $T_c\rightarrow 0$ gives $B_{c2}=(5.5\pm0.5)$ T for $R=0.5R_n$ (R_n is the normal-phase resistance) and $B_{c2}=(6.7\pm0.5)$ T for $R=0.9R_n$. In our experimental sample we thus have $B_c\cong B_{c2}$, and we can assume that the observed phase transition corresponds to the standard destruction of superconductivity by a magnetic field. The negative sign of the resistance dR/dT in the normal phase is explained by localization effects in the conductivity of the unpaired electrons. In Ref. 8 the data obtained for $R(B,T)$ in $Nd_{2-x}Ce_xCuO_4$ single crystals were interpreted in the same manner.

The logarithmic temperature dependence of the resistance which we observed in fields $B>B_c$ at temperatures $T\leqslant 10$ K (Fig. 2) corresponds to a 2D character of the conductivity with weak carrier localization. The logarithmic correction is $\cong 10\%$ at $T=1.3$ K with respect to the resistance at $T=10$ K. At the same time, if the expression for the conductivity of a 2D system in the regime of the mean free path l ($\hbar k_F$ is the Fermi momentum) is used[9]

$$\sigma_{\square}=(e^2/h)k_F l, \tag{7}$$

then setting $\sigma_{\square}^{-1}=R_{\square}\cong 1.2\ \mathrm{k}\Omega$ at $B=B_c$ and $T=10$ K, we obtain the estimate $k_F l \cong 20$. Even for such high values of the parameter $k_F l$ in a 2D system it turns out that the quantum corrections appearing in the metallic conductivity as a result of interference processes can be separated from the contribution of the electron-electron interaction. In fields $B>B_c$ the latter contribution apparently predominates, since the logarithmic term $R(T)$ is virtually independent of the magnetic field right up to $B\cong 10$ T (see Fig. 2).

The value which we obtained for the product of the critical exponents $z\nu = 1.1 \pm 0.1$ is close to the theoretical estimate for 2D systems on the basis of the scaling theory: $z=1$, $\nu \geqslant 1$ (see, for example, Ref. 10). This result is also in good agreement with the results of all experimental studies presented above [$\nu = 1.26$ and 1.31, $z = 0.98 \pm 0.04$ (Ref. 7); $z\nu = 1.2 \pm 0.1$ (Ref. 8); $\nu = 1.3 \pm 0.1$, $z = 1.0 \pm 0.1$ (Ref. 9)]. The critical exponent ν for the coherence length does not agree with the Ginzburg–Landau mean-field theory, where $\nu = 1/2$, irrespective of the dimension of the system.[10] Our value of ν allows us to conclude that, first, the phase transition which we observed is of a 2D character and, second, the long-wavelength fluctuations, which determine the scaling dependences (4) and (5) near the critical field in the 2D system, play a large role. It is well known that in 3D systems the fluctuation region near the superconducting transition is very narrow and is not observable experimentally (see, for example, Ref. 10).

In summary, after the destruction of superconductivity by a magnetic field our experimental $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ single crystal exhibits in the normal phase at temperatures $T \leqslant 10$ K several properties which are characteristic of weakly localized electrons in 2D systems. These properties, just as the strong anisotropy of the resistance at temperatures $T > T_c$, are a consequence of the pronounced layered structure of the crystal lattice of NdCeCuO.

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