Logarithmic Divergence of both In-Plane and Out-of-Plane Normal-State Resistivities of Superconducting $La_{2-x}Sr_xCuO_4$ in the Zero-Temperature Limit

Yoichi Ando,* G. S. Boebinger, and A. Passner
AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974

Tsuyoshi Kimura and Kohji Kishio
Department of Applied Chemistry, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113, Japan

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The low-temperature normal-state resistivities of underdoped $La_{2-x}Sr_xCuO_4$ crystals with T_c of 20 and 35 K were studied by suppressing the superconductivity with pulsed magnetic fields of 61 T. Both in-plane resistivity ρ_{ab} and out-of-plane resistivity ρ_c are found to diverge logarithmically as $T/T_c \rightarrow 0$. Logarithmic divergence is accompanied by a nearly constant anisotropy ratio, ρ_c/ρ_{ab}, suggesting an unusual three-dimensional insulator.

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The peculiarity of the high-T_c superconducting cuprates is readily apparent in the transport properties of the normal state. One striking aspect is the linear-T in-plane resistivity ρ_{ab}, which extrapolates to zero residual resistivity in samples exhibiting near-optimum T_c [1,2]. Another, equally unusual, behavior is that ρ_{ab} remains metallic while the out-of-plane resistivity ρ_c appears to diverge with decreasing temperature over a wide range of carrier concentration [1,3–6], a paradoxical behavior that has been argued to be contrary to Fermi liquids in the zero-temperature limit [7]. It is believed that the unusual properties of the normal-state resistivity reflect the electronic structure that underlies high-T_c superconductivity, although direct measurement of the low-temperature limiting behavior is obscured by the onset of superconductivity. It would, therefore, be interesting to suppress superconductivity and measure this electronic system in the zero-temperature limit in an attempt to resolve the paradox deduced from higher temperature experiments.

Recent experiments have utilized magnetic fields as high as 35 T to suppress superconductivity in cuprates with $T_c \sim 15$ K. In overdoped $Tl_2Ba_2CuO_6$ [8] and $Bi_2Sr_2CuO_y$ [9], a peculiar, rapidly increasing upper critical field is observed in the $T/T_c \rightarrow 0$ limit. In both systems, the normal state ρ_{ab} remains metallic at low temperatures.

In an effort to shed further light on the zero-temperature normal-state properties of high-T_c cuprates, we have suppressed the superconductivity in underdoped $La_{2-x}Sr_xCuO_4$ (LSCO) single crystals with a pulsed magnetic field of 61 T [10] applied along the c axis. A magnetic field of this intensity enables measurement of the normal state ρ_{ab} and ρ_c down to $T/T_c \sim 0.04$ in samples with T_c's as high as 35 K. We find that both ρ_{ab} and ρ_c show the *same* insulating behavior at low temperature, diverging as $\ln(1/T)$ over a wide range of temperatures below T_c. Furthermore, in contrast to the strong temperature dependence in the anisotropy ratio ρ_c/ρ_{ab} observed above T_c, we find that ρ_c/ρ_{ab} is essentially constant over the temperature range of the logarithmic divergence. This suggests a common transport mechanism and, therefore, anisotropic 3D transport [5,6] inconsistent with 2D Anderson localization [11].

The samples measured here are LSCO single crystals grown by the floating-zone method [4]. We studied two underdoped compositions, nominally $x = 0.08$ and 0.13, which have T_c (midpoint) of 20 and 35 K, respectively. (For LSCO, optimum $T_c \approx 40$ K occurs for $x \approx 0.16$ [4,12].) For each composition, two platelet-shaped crystals were prepared, one for ρ_{ab} measurement with the ab direction in the wide face, and the other one for ρ_c measurement along the c direction in the wide face. The crystals are typically $3 \times 2 \times 0.2$ mm^3. To assure a homogeneous current flow in the samples, current leads are attached to the side faces of the platelet. Zero-field and dc-field measurements are made by a low-frequency (17 Hz) four-probe technique. For the pulsed experiments, a transient digitizer records the fast (10 μsec) output of a lock-in driven at $\sim$120 kHz. No frequency dependence is observed in the data. The ac-current density (as much as 5 A/cm^2 for the lowest-impedance sample) was chosen to be as large as the contact and sample impedance allow, while avoiding any evidence of sample heating or non-Ohmicity.

Before each pulse, the sample is stabilized at a temperature in the $T = 0.7$ to 100 K range. The pulsed magnetic field is applied parallel to the c axis, rising sinusoidally to the maximum field $B_{\rm max}$ in $\sim$5 msec, staying within 1% of $B_{\rm max}$ for $\sim$1 msec, then decaying roughly exponentially to zero in about 80 msec. Because of the transient nature of the magnetic field, we carefully check for evidence of sample heating during the pulse, primarily by comparing a series of fixed-temperature pulses with different $B_{\rm max}$. Since eddy-current heating varies as $(dB/dt)^2$, sample heating during the pulse is readily apparent if the data from different $B_{\rm max}$ pulses do not agree or if the low field pulsed data do not reproduce dc-field data. No evidence of sample heating is observed in the

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presented data, except as noted for T just above 4.2 K, particularly in the $x = 0.13$ samples (due, in part, to the lower ρ_{ab} in the plane perpendicular to B).

Figure 1 shows the magnetic-field dependence of ρ_{ab} for $x = 0.08$ for T from 0.7 to 24 K. All traces are the raw data taken during the down sweep of the magnetic field. Although the transition is broad, it is apparent that a 61-T magnetic field is sufficient to suppress superconductivity in this sample, even down to 0.7 K. This is particularly evidenced by the negative magnetoresistance (MR) observed at high magnetic fields in the normal-state resistivity ρ_{ab} for all temperatures below ~24 K. Measurements of ρ_c, for which $I \parallel B \parallel c$, also exhibit negative MR at low temperatures, although the onset of negative MR occurs at ~50 K. With a sample exhibiting such a large anisotropy, concern might arise that measurements in the ρ_c geometry, in fact, detect ρ_{ab} due to a circuitous current path dominated by carrier conduction in the a-b planes. The different onset temperatures for negative MR offer compelling evidence that this is not the case. This conclusion is further supported by the measurements on the $x = 0.13$ samples, where the high-field negative MR is observed below ~45 K in ρ_c but is never observed in ρ_{ab}, even at 1.4 K.

Negative MR in ρ_c has been reported for the double-layer materials, $Bi_2Sr_2CaCu_2O_{8+\delta}$ [13,14] and $YBa_2Cu_3O_{7-x}$ [13]. It has been interpreted by Yan *et al.* [13] in terms of a spin gap or pseudogap, which blocks c axis conduction. In their analysis of c axis data, a magnetic field suppresses the pseudogap. To extend this idea to our ρ_{ab} data, we first note that the formation of a pseudogap has been associated with a *reduction* in ρ_{ab} [15,16]. Thus a magnetic field that suppresses the pseudogap would yield a *positive* MR in ρ_{ab}, in contrast to Fig. 1.

Figure 2 shows the temperature dependence of ρ_{ab} for $x = 0.08$ at fixed magnetic fields, determined from a series of nineteen 61-T pulses. It is apparent that a superconductor-to-insulator (S-I) transition occurs upon applying a magnetic field, with no evidence of an intervening metallic phase (see inset). The data are consistent with a crossover to an insulating state at a mean-field upper critical field $H_{c2}(0) \sim 40$ T [17]. Because the 50- and 60-T data are nearly identical, we believe we are measuring the true normal-state resistivity at our highest fields. This is further evidenced by the agreement between the pulsed and zero-field data above T_c.

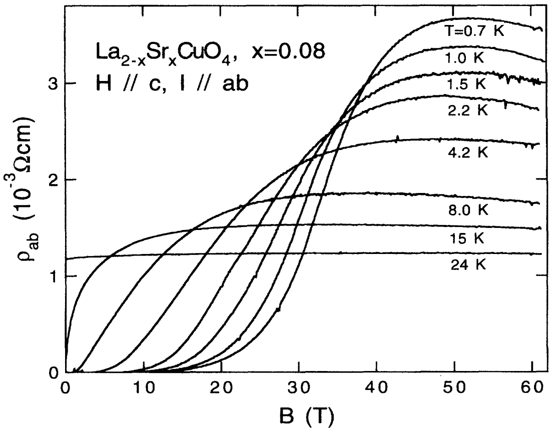

FIG. 1. In-plane resistivity ρ_{ab} versus magnetic field for the $x = 0.08$ $La_{2-x}Sr_xCuO_4$ single crystal at various temperatures.

We turn attention to the precise temperature dependence of the normal-state resistivity. A variety of functional forms do not fit the diverging normal-state resistivity, including thermal activation ($\ln\rho \sim -1/T$), various types of variable range hopping (VRH) conduction ($\ln\rho \sim T^{-\beta}$ with $\beta = \frac{1}{2}, \frac{1}{3}, \frac{1}{4}$), and power-law dependence ($\ln\rho \sim \ln T$). Instead, the data from all four samples exhibit a $\ln(1/T)$ divergence [$\rho \sim \ln(1/T)$] over most of the temperature range below T_c, as shown in Fig. 3. The logarithmic behavior (dashed lines) is particularly evident in the $x = 0.08$ data, in which it extends over a temperature range of about one-and-a-half decades [18]. The slight downward deviation from $\ln(1/T)$ dependence at the lowest temperatures in Figs. 3(c) and 3(d) results from the proximity of the superconducting transition, which can be clearly seen in the 50-T data of Fig. 3(d).

Because the magnetic-field dependence of the normal-state resistivity is very small compared to the temperature dependence, we find it reasonable to conclude that the $\ln(1/T)$ dependence mimics the behavior of the high-T_c electron system at zero magnetic field in the absence of superconductivity. If so, the $x = 0.13$ data is particularly striking (see Fig. 4) because ρ_{ab} shows linear-T behavior above 150 K, which extrapolates to a zero intercept (dotted line), yet ρ_{ab} crosses over to logarithmic insulating behavior at low temperatures (dashed line). Even for this sample, in which the dynamic range of the logarithmic divergence is particularly limited, the qualitative determination of $\ln(1/T)$ behavior is not dependent on whether

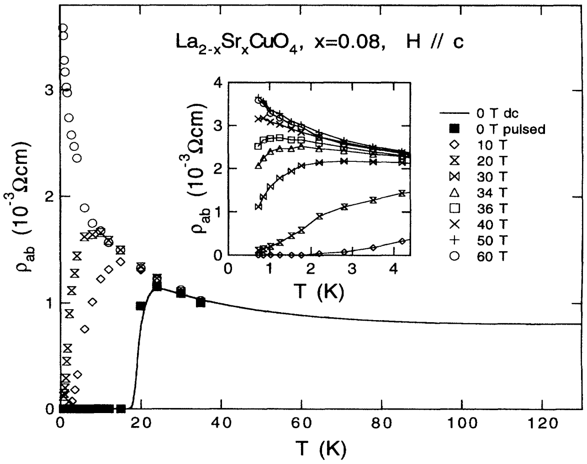

FIG. 2. Temperature dependence of ρ_{ab} in 0, 10, 20, and 60 T, obtained from the pulsed magnetic field data. The solid line shows the zero-field resistive transition. The inset contains the low-temperature data.

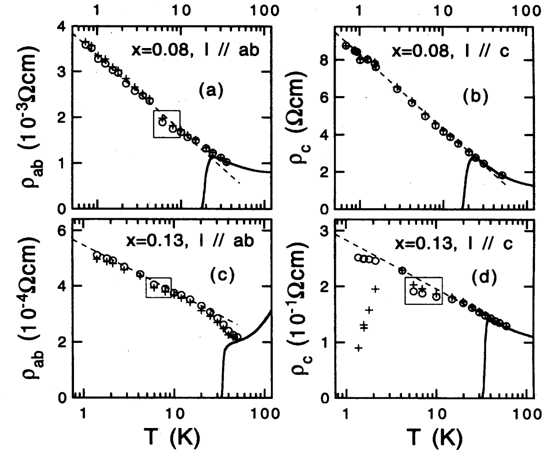

FIG. 3. Resistivity vs ln$T$ plots from all four samples: (a) ρ_{ab} and (b) ρ_c for $x = 0.08$; (c) ρ_{ab} and (d) ρ_c for $x = 0.13$. Circles and crosses denote the 60- and 50-T data, respectively; the thick line is the zero-field data. Boxes enclose those few points from magnetic field traces that show evidence of sample heating during the pulse. The dashed lines show the fits to the low-temperature logarithmic divergences [18]. Note in (c) that low-temperature $\ln(1/T)$ behavior can occur even when ρ_{ab} is metallic over the entire temperature range above T_c.

the linear-T contribution (dotted line) is subtracted from the raw data.

Figure 5 contains a plot of the anisotropy ratio ρ_c/ρ_{ab}, which is strongly temperature dependent at high temperatures. It is clear that the normal-state anisotropy ratio becomes essentially temperature independent over the entire temperature range of $\ln(1/T)$ behavior. This implies that the carrier-transport mechanism in the low-temperature limit is the same for the ab and c directions when the normal-state resistivity diverges logarithmically. We emphasize that the magnitude of the MR mentioned earlier, whether positive or negative, is sufficiently small ($<5\%$ of the resistivity) that the magnetic-field dependence of ρ_c/ρ_{ab} is negligible on this scale.

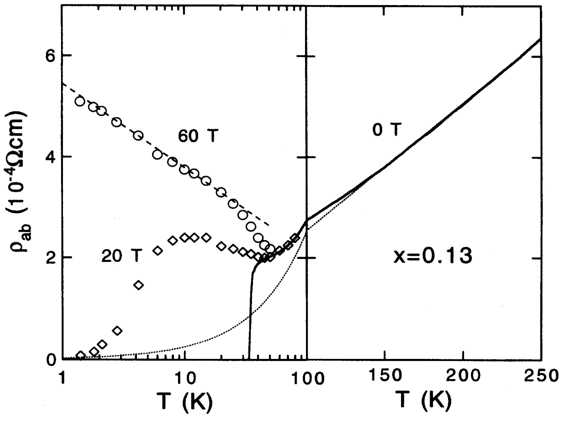

FIG. 4. In-plane resistivity ρ_{ab} for the $x = 0.13$ sample plotted vs linear T at high temperature and ln$T$ at low temperature. Data are shown for $B = 0$ T (solid line), 20 T (diamonds), and 60 T (circles) with the logarithmic fit shown as a dashed line. The dotted line is the extrapolated linear-T dependence.

We note that our results contrast with measurements made on insulating LSCO. When the Sr concentration is reduced below $x \sim 0.05$, LSCO becomes insulating [2,12]. For such LSCO samples, the low-temperature ρ_{ab} is orders of magnitude larger and consistent with variable range hopping of localized holes [19,20]. These results do not directly conflict with ours on superconducting LSCO, in which the measured ρ_{ab} remains below the unitarity scattering limit [21], even for our most resistive data [22]. Rather, the normal state might be fundamentally different between superconducting LSCO and insulating LSCO.

Now let us discuss possible origins for the $\ln(1/T)$ insulating behavior. We can probably exclude the Kondo effect, which can give rise to a large $\ln(1/T)$ dependence in resistivity due to magnetic impurities: a magnetic field of 60 T would preclude spin-flip scattering (and, thus, logarithmic behavior) below $k_BT \sim g\mu_BB$, that is, $T < 40$ K.

The marginal Fermi liquid model [23] for the normal-state properties of high-T_c cuprates predicts a leading $\ln(T_0/T)$ correction to the resistivity when quasiparticle-impurity scattering dominates conduction [24], with T_0 the same in all directions. This prediction results from the same hypotheses that give a linear-T dependence of ρ_{ab} at high temperatures. The model conjectures a 3D insulating state at low temperatures; however, calculations to date give a $[\ln(1/T)]^2$ low-temperature divergence [24].

We note that logarithmic behavior of in-plane conductivity σ_{ab} has been reported in LSCO with lower T_c [25], in (electron-doped) $Nd_{2-x}Ce_xCuO_y$ [26], and in nonsuperconducting $Bi_2Sr_2CuO_y$ [27,28]. In all these experiments, the temperature dependence of σ_{ab} appears at first sight to be consistent with 2D weak localization [29]. However, in both Refs. [25] and [28], the MR has been examined in detail and found to be inconsistent with the usual weak localization of a Fermi liquid. Our data give additional evidence against 2D weak localization, since the same $\ln(1/T)$ behavior is observed along the c axis. Electron interactions in 2D systems can also give rise to

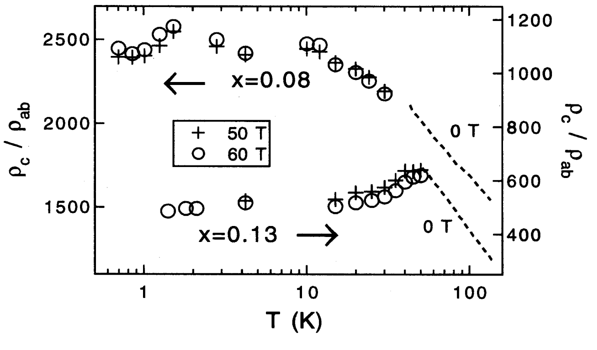

FIG. 5. Anisotropy ratio ρ_c/ρ_{ab} for $x = 0.08$ and 0.13 at low temperatures in high fields, together with zero-field ρ_c/ρ_{ab} above T_c (dashed lines).

a logarithmic correction in σ_{ab}, not through localization, but by modifying the 2D density of states [30]. If ρ_c is determined by tunneling between 2D systems, this modification of the 2D density of states might account for the same $\ln(1/T)$ behavior being observed in ρ_c [31]. However, a discrepancy remains between existing calculations and the data of Fig. 3: plots of σ_{ab} $(= 1/\rho_{ab})$ vs $\ln T$ are not at all linear, due to the range of resistivity over which logarithmic behavior is observed.

To summarize, by suppressing superconductivity with 61-T magnetic field, we find a logarithmic divergence of the normal-state resistivity of underdoped LSCO in the zero-temperature limit, $T/T_c \rightarrow 0$, which contrasts with the metallic behavior previously reported for overdoped cuprates. In the $T_c = 35$ K sample, this behavior coexists with linear-T in-plane resistivity at high temperatures. While the anisotropy ρ_c/ρ_{ab} is strongly temperature dependent above T_c, it becomes essentially constant over the same temperature range as the logarithmic divergence. These observations strongly suggest that superconducting LSCO in the underdoped regime is an anisotropic 3D insulator in the low-temperature limit in the absence of superconductivity.

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*Permanent address: Central Research Institute of Electric Power Industry, 2-11-1 Iwato-kita, Komae, Tokyo 201, Japan.

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