c-axis longitudinal magnetoresistance of the electron-doped superconductor
Pr$_{1.85}$Ce$_{0.15}$CuO$_4$

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We report c-axis resistivity and longitudinal magnetoresistance measurements of superconducting Pr$_{1.85}$Ce$_{0.15}$CuO$_4$ single crystals. In the temperature range 13K $\leq T \leq 32$K, a negative magnetoresistance is observed at fields just above $H_{c2}$. Our studies suggest that this negative magnetoresistance is caused by superconducting fluctuations. At lower temperatures ($T \leq 13$K), a different magnetoresistance behavior and a resistivity upturn are observed, whose origin is still unknown.

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Both electron-doped (n-type) and hole-doped (p-type) cuprate superconductors show many interesting properties. One important question is the particle-hole symmetry, that is, whether the phenomena observed in the hole-doped cuprates are the same as those observed in the hole-doped cuprates. The study of this issue may improve our understanding of their normal state properties and the origin of high-temperature superconductivity.

C-axis transport has been shown to be a useful measurement for electronic properties, and a comparison of c-axis transport in both types of cuprate superconductors is in progress. For example, a four-fold oscillation of the c-axis angular magnetoresistance has been reported in underdoped n-type cuprates, which suggests a stripe-like structure as in the p-type cuprates. C-axis transport is also a good probe of the electron density of states (DOS) at the Fermi surface close to $(\pi, 0)$ in the tetragonal cuprates, because of its intrinsic interlayer tunneling nature and a transfer integral effect. A pseudogap, indicated by a loss of electronic DOS, has been observed by c-axis transport in both the p-type cuprates. C-axis transport is caused by superconducting fluctuations. At lower temperatures ($T \leq 13$K), a different magnetoresistance behavior and a resistivity upturn are observed, whose origin is still unknown.

In the underdoped ($x<0.15$) n-type cuprates, a rapid decrease of the low-temperature c-axis resistivity, compared to the ab-plane resistivity, is consistent with a coherent transport at $(\pi, 0)$ and a high-energy ($\sim 100$ meV) pseudogap at $(\pi/2, \pi/2)$, as shown by ARPES, optical, and other transport measurements. This pseudogap is likely caused by antiferromagnetic ordering or a spin density wave (SDW) up to a doping level $x=0.15$. The pseudogap in the p-type compounds, as shown by a large c-axis resistivity upturn and a negative magnetoresistance, is very prominent. Indeed, two types of pseudogaps are suggested in different regimes. A small-energy gap is consistent with a precursor pairing or superconducting fluctuation scenario. A large-energy pseudogap opens at $(\pi, 0)$, which is unlikely to be correlated with superconductivity although the origin is still being debated.

In this work, we studied the low temperature c-axis resistivity and longitudinal magnetoresistance of optimally electron-doped Pr$_{1.85}$Ce$_{0.15}$CuO$_4$ (PCCO) single crystals. For the temperature range $13K \leq T \leq 32$K, we found a negative magnetoresistance in a field range $H < H_p(T)$ (defined later), $H_p(T)$ is higher than $H_{c2}(T)$ and increases as temperature decreases. Our detailed studies suggest that this high-temperature n-MR is caused by superconducting fluctuations in a quasi-2D system. For lower temperatures $T < 13$K, a different magnetoresistance behavior and a resistivity upturn are observed, the origin of which is still unclear.

The PCCO single crystals were grown by the self-flux method and the usual oxygen reduction procedure was followed to achieve superconductivity. The crystals are plate-like with size $\sim 0.5 \times 0.5 \times 0.03 \text{mm}^3$. The sharp superconducting transition ($T_C = 23.5 \pm 0.75$K) found by SQUID magnetization measurements indicates a high crystal quality. For resistivity, a conventional four-wire method was used...
At zero field, the superconducting transition occurs at $H = 0$. For $10K \leq T \leq 32K$, the low-temperature magnetoresistance at $2K \leq T \leq 13K$.

The temperature dependence of the c-axis resistivity of an optimally doped PCCO crystal is shown at various longitudinal magnetic fields $H \parallel C$ in Fig. 1. At zero field, the superconducting transition occurs at $T_C \approx 25K$ as indicated by zero resistivity. At low fields $(\mu_0 H \leq 2.5T)$, a small upturn feature in the c-axis transport is seen just above the superconducting transition. This resistivity minimum shifts to lower temperature as the field increases. At high fields ($H \geq H_{C2}$), the resistivity shows a strong upturn feature as temperature decreases below $T \approx 13K$.

We find that the magnetoresistance behaviors are different in the temperature range above and below $T = 13K$. The c-axis longitudinal magnetoresistance is shown in Fig. 2. For clarity, we plotted $\rho_C(H, T)$ versus $(\mu_0 H)^2$. At $T > 32K$, the magnetoresistance, $\Delta \rho_C(H, T) = \rho_C(H, T) - \rho_C(0, T)$, is positive and proportional to $H^2$ at high temperatures (data not shown). With decreasing temperature from $32K$ to $13K$, a deviation from the $H^2$ behavior develops at low field, and a negative magnetoresistance (n-MR) appears close to zero field. For $T < T_C$, the n-MR is more evident, so that a resistivity peak forms as superconductivity is suppressed. The n-MR extends to higher fields as temperature drops. Below $13K$, a different magnetoresistance behavior is observed, as seen by the suppression of the n-MR and disappearance of the resistivity peak at $T < 8K$ (Fig. 2 inset).

This different magnetoresistive behavior in the temperature range below and above $13K$ can be explained as arising from two contributions. The high-temperature n-MR comes from superconducting fluctuations, whereas the low-temperature magnetoresistance behavior and the resistivity upturn come from another mechanism of unknown origin. In the following, we discuss these two contributions separately.

We first discuss the origin of the n-MR behavior for $T > 13K$. In Fig. 2 we define $H_{peak}$ as the field corresponding to the resistivity peak, and $H_P$ as the lowest field where $\Delta \rho_C(H, T) \sim H^2$ is obeyed. In Fig. 3 the values of $H_{peak}$ and $H_P$ at different temperatures are shown. Therefore, the n-MR exists between $H_P$ and $H_{peak}$. $H_P$ emerges at $T^* = 32K$, which is slightly above $T_C$. As temperature decreases, the temperature dependence of $H_P$ suggests that it extrapolates to $\mu_0 H_P \approx 10T$ at $T = 0$. We did not measure $H_{C2}$ on our crystal, but a recent Nernst effect measurement on an optimally doped NCCO crystal ($T_C \approx 24.5K$) gave $\mu_0 H_{C2} \approx 6T$ at $13K$, which is below our value of $\mu_0 H_P \approx 10T$ at $13K$. The slightly higher value of $T^*$ ($H_P$) than that of $T_C$ ($H_{C2}$), suggests that the c-axis n-MR is associated with superconducting fluctuations.

We now show that the doping dependence of the n-MR supports our view that the n-MR for $T \geq 13K$ originates from superconducting fluctuations. Although PCCO crystals with other doping levels were not available for our c-axis measurements, we measured an as-grown (unannealed), non-superconducting, $Pr_{1.85}Ce_{0.15}CuO_{4+\delta}$ crystal. Neutron scattering studies have shown that this unannealed crystal is equivalent to an antiferromag-
grown, non-superconducting, Pr$_{1.88}$Ce$_{0.12}$CuO$_4$ crystal. As shown in the inset of Fig. 4, a resistivity upturn is clearly seen at $T \leq 60K$, which is indicative of antiferromagnetic ordering. Moreover, a positive magnetoresistive behavior is seen at all temperatures below $T = 60K$ as shown in Fig. 4. The absence of the n-MR in this effectively underdoped crystal suggests that the n-MR is unlikely to be correlated with antiferromagnetism or a spin pseudogap state. The appearance of the n-MR only in the superconducting crystals strongly supports our interpretation of superconducting fluctuations as the origin of the n-MR.

A qualitative comparison between the ab-plane and the c-axis magnetoresistance confirms our interpretation of superconducting fluctuations for $T \geq 13K$. We measured the transverse magnetoresistance of the ab-plane transport with $H \parallel C$ and compared it with the c-axis longitudinal magnetoresistance at a specific temperature 16K as shown in Fig. 5(a). The ab-plane magnetoresistance is positive and increases linearly with field above 8T. To estimate the deviation of the low-field magnetoresistance, we subtracted a fit to the high-field magnetoresistance for both transports, as shown in Fig. 5(b). Below $\mu_0 H = 8T$, the c-axis transport shows a negative magnetoresistance (Fig. 5(a) inset), whereas the ab-plane transport shows a positive magnetoresistance (Fig. 5(b) inset). This distinctive c-axis and the ab-plane magnetoresistance can be explained by an Aslamazov-Larkin (AL) contribution from fluctuating Cooper pairs and a density of states (DOS) contribution from electrons in a highly anisotropic superconductor. When increasing the field above $H_{c2}$, the suppression of superconducting fluctuations causes a decrease of the ab-plane conductivity from the reduced AL contribution, and an increase of the c-axis tunneling conductivity from the resulting increase of the electronic DOS.

To summarize, the appearance of a c-axis n-MR only in superconducting PCCO crystals in fields (temperature) just above $H_{c2}$ ($T_C$) suggests that the n-MR is due to superconducting fluctuations. The contrasting c-axis and ab-plane magnetoresistance in the same field (temperature) range can be understood by an AL process and a reduction of electronic DOS due to superconducting fluctuations in a quasi-2D system. The c-axis n-MR of PCCO is rather similar to that found in the p-type superconductor Bi-2201$^{29}$, which has been interpreted to be caused by superconducting fluctuations. The only difference is that superconducting fluctuations in PCCO seem to occur in a smaller range of temperature and field. Our n-MR does not seem to be related to the low-energy normal-state tunneling gap$^{24,25,26,27}$, because the tunneling gap is also found for $x = 0.11$ where we see only positive magnetoresistance.

Now we discuss the low-temperature c-axis resistivity and magnetoresistance. Both a different magnetoresistance behavior (see Fig. 2 inset) and a strong resistivity upturn (see Fig. 1) occur below 13K. This suggests that the resistivity and the magnetoresistance are correlated. It may be related to the same mechanism which causes the resistivity upturn in the ab-plane transport. Recently Kawakami et al.$^{28}$ reported a negative c-axis magnetoresistance (n-MR) in optimally doped n-type Sm$_1.45$Ce$_{0.15}$CuO$_4$ (SCCO) up to 40T and down to 0.5K. Since n-MR has been observed in both the p-type and the n-type cuprates, they associated the n-MR with a universal Zeeman-splitting effect of a spin pseudogap in both systems. For comparison, the absence of the n-MR and

FIG. 4: The c-axis longitudinal magnetoresistance of an as-grown, non-superconducting, Pr$_{1.88}$Ce$_{0.12}$CuO$_4$ crystal. Inset: temperature dependence of the c-axis resistivity.

FIG. 5: (a) The c-axis longitudinal magnetoresistance of a PCCO crystal at $T = 16K$. The solid line is a fit to high-field magnetoresistance ($\propto H^2$). Inset: the low-field n-MR found by subtracting off the high-field fit. (b) The ab-plane transverse magnetoresistance of the PCCO crystal at $T = 16K$. The solid line is a fit to the high-field magnetoresistance ($\propto H$). Inset: the low-field positive magnetoresistance found by subtracting off the high-field fit.
the resistivity peak below 14T in our PCCO crystals (see Fig. 2 inset) is different from that observed by Kawakami et al.\textsuperscript{29} in SCCO. Currently, we are not able to verify their spin pseudogap interpretation of the n-MR because we lack sufficient high-field, low-temperature, data. As presented earlier, our high-temperature n-MR is most likely caused by superconducting fluctuations.

In summary, we have studied the c-axis resistivity and magnetoresistance on optimally doped Pr\textsubscript{1.85}Ce\textsubscript{0.15}CuO\textsubscript{4} crystals. Different resistivity and magnetoresistance behavior in two temperature ranges, suggests that two contributions should be considered to understand the c-axis transport. For 13K≤T≤32K, a n-MR, which exists only in the superconducting crystals in fields just above $H_{C2}$, is most likely caused by superconducting fluctuations. A distinctive c-axis negative-magnetoresistance and an ab-plane positive-magnetoresistance is found, which can be explained by an Aslamazov-Larkin process and a reduction of electronic DOS in a highly anisotropic superconductor. For T<13K, a different magnetoresistance behavior and a resistivity upturn are observed, the origin of which is unclear at present.

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