Non-Universal Power Law of the “Hall Scattering Rate” in a Single-Layer Cuprate Bi$_2$Sr$_{2-x}$La$_x$CuO$_6$

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(Received BSCO-3.tex)

In-plane resistivity, Hall coefficient, and magnetoresistance (MR) are measured in a series of high-quality Bi$_2$Sr$_{2-x}$La$_x$CuO$_6$ crystals with various carrier concentrations, from underdope to overdope. It is found that the temperature dependence of the Hall angle obeys a power law $T^\alpha$ with $\alpha$ systematically decreasing with increasing doping, which questions the universality of the Fermi-liquid-like $T^2$ dependence of the “Hall scattering rate”. The systematics of MR indicates an increasing role of spin scattering in underdoped samples.

PACS numbers: 74.25.Fy, 74.62.Dh, 74.72.Hs

The peculiar normal-state properties of high-$T_c$ cuprates are generally considered to be the keys to elucidate the high-$T_c$ mechanism, since they give us a clue to clarify the nature of the strongly-correlated electronic state of the cuprates. To understand the underlying electronic state of the cuprates, it is desirable to study the normal state at low temperatures\cite{1} and to chase the systematic evolution thereof with carrier concentration\cite{2}. Therefore, particularly useful system for the normal-state of the cuprates, it is desirable to study the electronic state of the cuprates, to understand the underlying electronic interactions in the scattering mechanism. In high-$T_c$ cuprates, it has been discussed that the charge transport is governed by two different scattering times with different temperature dependences\cite{3,4}: according to this “two-scattering-time” model, in-plane resistivity $\rho_{ab}$ is governed by the transport scattering time $\tau_{tr}$ ($\sim T^{-1}$) and the Hall angle $\theta_H$ is governed by the “Hall scattering time” $\tau_H$ ($\sim T^{-2}$). However, this idea of “scattering-time separation” has not yet gained a complete consensus and there are other approaches to understand the unusual normal-state transport properties\cite{5,6}. Therefore, it would be useful to establish the temperature and doping range in which the $T^2$ behavior of the Hall scattering rate $\tau_H^{-1}$ is observed.

There are two widely-known cuprate systems which satisfy the requirements of the relatively low $T_c$ and the availability of a wide doping range: La$_{2-y}$Sr$_y$CuO$_4$ (LSCO) system and Bi-2201 system. Bi-2201 has not been as intensively studied as LSCO, mostly because of the difficulty in obtaining high-quality single crystals. A number of problems have been known for Bi-2201 crystals: (a) the transport properties of B-2201 are quite non-reproducible even among crystals of nominally the same composition\cite{1,2}; (b) the residual resistivity of the in-plane resistivity $\rho_{ab}$ is usually large (the smallest value reported to date is 70 $\mu\Omega$cm\cite{2,3}), as opposed to LSCO, YBa$_2$Cu$_3$O$_7$ (YBCO), or Bi$_2$Sr$_2$CaCu$_2$O$_8$ (Bi-2212), where the residual resistivity in high-quality crystals is negligibly small; and (c) the temperature dependence of the Hall coefficient is weak and thus the Hall angle $\theta_H$ does not obey the $T^2$ law\cite{4,10,11}, while $\theta_H \sim T^2$ has been almost universally observed in other cuprates\cite{10}. On the other hand, the Bi-2201 system has very attractive characteristics: it has been known for Bi-2201 that the carrier concentration can be widely changed by partially replacing Sr with La (to underdope) or Bi with Pb (to overdope)\cite{2}; at optimum doping (Bi$_2$Sr$_{2-x}$La$_x$CuO$_6$ with $x \approx 0.4$), the maximum $T_c$ is about 30 K\cite{2,3}, which is lower than the maximum $T_c$ of LSCO. Therefore, if single crystals of sufficiently high quality are grown, this system would present an ideal stage for the systematic study of the normal-state properties down to lower temperatures than in other cuprates.

In this Letter, we report that it is possible to obtain a series of high-quality Bi-2201 crystals and show that in those high-quality crystals the normal-state transport properties display behaviors which are in good accord with other cuprates; for example, in the underdoped region, $\rho_{ab}$ shows a downward deviation from the $T$-linear behavior at a certain temperature which decreases with increasing doping and, in the overdoped region, $T$ dependence of $\rho_{ab}$ changes to $T^n$ with $n > 1$. What is new in this system is that the Hall angle indeed obeys a power law $T^\alpha$ with $\alpha \approx 2$, but the power $\alpha$ shows a systematic decrease towards smaller values as the carrier concentration is increased. This finding of a systematic change of $\alpha$ in a relatively-simple single-layer cuprate system poses a serious question to the universality of the “Fermi-liquid like” $T^2$ behavior of the Hall scattering rate $\tau_H^{-1}$\cite{4,3}. Another notable finding is that the ratio of the longitudinal magnetoresistance (MR) to the transverse MR increases systematically with decreasing carrier concentration, in-

arXiv:cond-mat/9812334v1 [cond-mat.supr-con] 21 Dec 1998
indicating that a spin contribution to the MR gradually becomes significant as the sample becomes more underdoped.

The single crystals of Bi$_2$Sr$_2$-xLa$_x$CuO$_6$ (BSLCO) are grown using a floating-zone technique in 1 atmosphere of flowing oxygen. It is known that pure Bi-2201 is an overdoped system \cite{12}. Since the La substitution to the Sr site reduces the number of holes, increasing La doping brings the system from overdoped region to underdoped region. We found that the La substitution results in a growth of crystals of better morphology compared to the pure Bi-2201. The actual La concentrations in the crystals are determined by the inductively-coupled plasma spectrometry (ICP) technique. Here we report crystals with $x=0.24, 0.30, 0.44, 0.57, \text{ and } 0.66,$ for which the zero-resistance $T_c$ (and the mid-point $T_c$) as a function of $x$. Apparently, $x\geq 0.4$ corresponds to the optimum doping, which is consistent with previous reports on BSLCO \cite{12,13}. The onset of the Meissner effect (measured with a commercially available Quantum Design SQUID magnetometer) for the optimally-doped crystals is 33 K. To our knowledge, this is the smallest value ever reported for pure Bi-2201 or BSLCO system. The ICP analysis found that our crystals are Bi-deficient by about 0.2, while Sr+$\text{La}$ is almost stoichiometric; for example, the $x=0.44$ sample has the composition of Bi$_{1.8}$Sr$_{1.57}$La$_{0.44}$CuO$_{6+\delta}$.

![Graph](image)

**FIG. 1.** $T$ dependence of $\rho_{ab}$ of the BSLCO crystals. Inset: $T_c$ as a function of La content $x$. The dashed lines are guide to the eyes.

The crystals are cut into a rectangular shape with typical size of $2 \times 1 \times 0.015 \text{ mm}^3$. The thickness of the crystals is accurately determined by measuring the weight of the sample with $0.1 \mu\text{g}$ resolution; therefore, the uncertainty in determining the magnitude of the resistivity is less than $\pm 5\%$. The crystals are annealed at 400°C for 30 minutes in flowing oxygen upon firing silver epoxy. We use a standard six-terminal method for simultaneous magnetoresistance (MR) and $R_H$ measurements, in which the data are taken with an ac technique in the sweeping magnetic field at fixed temperatures. The temperature is very carefully controlled and stabilized using both a capacitance sensor and a Cernox resistance sensor to avoid systematic temperature deviations with magnetic fields. The stability of the temperature during the MR and $R_H$ measurements is within a few mK.

Figure 1 shows the temperature dependence of $\rho_{ab}$ for the five $x$ values in zero field. Clearly, both the magnitude of $\rho_{ab}$ and its slope show a systematic decrease with increasing carrier concentration (decreasing $x$). We found that it is only at the optimum doping that $\rho_{ab}$ shows a perfect $T$-linear behavior. Figure 2 shows the temperature dependence of the slope $d\rho_{ab}/dT$; only the $x=0.44$ sample shows a constant $d\rho_{ab}/dT$, which corresponds to the $T$-linear behavior, in a wide temperature range (from 300 K to 120 K). We note that a fitting of the $\rho_{ab}$ data of the $x=0.44$ sample to $\rho_{ab}=\rho_0+AT^n$, which, to our knowledge, is the smallest value ever reported for pure Bi-2201 or BSLCO.

![Graph](image)

**FIG. 2.** $T$ dependence of the slope $d\rho_{ab}/dT$. The dashed line represents a constant slope ($T$-linear behavior). Inset: Plot of $\log(\rho_{ab}/\rho_0)$ vs $\log T$ for three $x$ values to show the power-law dependence $\rho_{ab}=\rho_0+AT^n$, which is represented by dotted lines.
The underdoped samples \((x=0.57\) and \(0.66)\) show a rather complex temperature dependence in \(\rho_{ab}\), which is similar to that of underdoped YBCO [4]; the behavior in underdoped YBCO is characterized by a downward deviation from the \(T\)-linear dependence and the presence of a maximum in \(d\rho_{ab}/dT\). Such a behavior has been correlated to the opening of a pseudogap [4]. The broad maximum in \(d\rho_{ab}/dT\) moves to higher temperature as the carrier concentration is decreased, which agrees with the conjecture that the pseudogap opens at higher temperature in more underdoped samples. On the other hand, the slope \(d\rho_{ab}/dT\) of the overdoped samples \((x=0.30\) and \(0.24)\) monotonically decreases with decreasing temperature. This reflects the fact that \(\rho_{ab}\) of the overdoped samples behaves as \(\rho_{ab}=\rho_0+AT^n\) with \(n\) larger than 1, a behavior reported in the overdoped samples of LSCO [15] and \(Tl_2Ba_2CuO_6+\delta\) (Ti-2201) [16]. The inset to Fig. 2 shows that \(\rho_{ab}(T)\) for \(x=0.30\) and 0.24 can actually be described by the power law with \(n=1.14\) and 1.27, respectively. Therefore, in both the underdoped and overdoped regions, the behavior of \(\rho_{ab}(T)\) shows an evolution which can be considered to be “standard” for high-\(T_c\) cuprates. This observation indicates that Bi-2201 is not an exceptional system but rather is a promising system for the systematic study of the normal-state transport properties.

![Figure 3](image-url)

**FIG. 3.** (a) \(T\) dependence of \(R_H\) of the BSLCO crystals. (b) Plot of \(\cot \theta_H\) vs \(T^2\) (the data for \(x=0.30\) and 0.24 are shifted down by 50 and 100, respectively, to avoid congestion). The solid line is a fit to the \(x=0.66\) data.

Figure 3(a) shows the temperature dependence of \(R_H\) for the five samples. A clear evolution of \(R_H\) with \(x\) is observed; the change in the magnitude of \(R_H\) at 300 K suggests that the carrier concentration is actually reduced roughly by a factor of 3 upon increasing \(x\) from 0.24 to 0.66. Figure 3(b) shows the plot of \(\cot \theta_H (=\rho_{xx}/\rho_{xy})\) vs \(T^2\). Only the data for \(x=0.66\) can be fitted with a straight line in this plot, indicating that the \(T^2\) law of \(\cot \theta_H\) holds only in this most underdoped sample. We found that \(\cot \theta_H\) for other \(x\) values obey a power law \(T^\alpha\) with \(\alpha\) smaller than 2, which is shown in Figs. 4 (a) - (d). The best powers are 1.85, 1.70, 1.65, and 1.60, for \(x=0.57, \ 0.44, \ 0.30, \ and \ 0.24), \ respectively. In all the panels of Fig. 4, the data are very well fitted with straight lines. Therefore, the power-law temperature dependence of the Hall scattering rate \(\tau_H^{-1}\) holds for every doping in BSLCO, but the power \(\alpha\) shows a systematic decrease with increasing carrier concentration [17]. A particularly intriguing fact here is that \(\cot \theta_H\) of the optimally-doped sample changes as \(T^{1.70}\), not as \(T^2\), while \(\rho_{ab}\) shows a good \(T\)-linear behavior. This might mean that the “Fermi-liquid like” behavior of \(\tau_H^{-1}\sim T^2\) (which has been proposed to be the characteristic of spinons [2]) may not be a generic feature of the optimally-doped cuprates.

![Figure 4](image-url)

**FIG. 4.** Plots of \(\cot \theta_H\) vs \(T^\alpha\) for the data of (a) \(x=0.57\), (b) \(x=0.44\), (c) \(x=0.30\), and (d) \(x=0.24\). The solid lines are fits to the data.

Figure 5 shows the transverse and longitudinal MR of four of the samples, \(x=0.24, 0.44, 0.57,\) and \(0.66). One may immediately notice a trend that the relative magnitude of the longitudinal MR compared to the transverse MR increases with increasing \(x\). (We omit the result of \(x=0.30\) due to the limited space; the behavior of this sample fits well into the trend.) Since it is expected that the longitudinal MR mostly comes from a spin contribution (while the transverse MR consists of both an orbital and the spin contribution), our result suggests that the role of spins in the transport becomes increasingly significant as the sample becomes more underdoped.
might be the reason for the relatively low freedom is already weakened at optimum doping, which turn suggests that in Bi-2201 the role of spin degrees of contribution to the charge transport is strong. This in that the tematic change of the longitudinal MR, might suggest range studied. This observation, combined with the sys- 
ics of the power law of the scattering rates (τ), details of the MR analysis will be published elsewhere. 

The above results tell us altogether that the systemat-
ics of the power law of the scattering rates (τ<sup>1</sup>) needs to be reconsidered. In particular, (τ<sup>−1</sup>) is strongly violated, as in other cuprates. We also found that the “modified Kohler’s rule” (τ<sup>−1</sup>~(cot θ<sub>H</sub>)<sup>−2</sup>) is not very well applicable to our data; this is different from the results for LSCO and YBCO and might be related to the fact that cot θ<sub>H</sub> does not behave as T<sup>2</sup> except for the x=0.66 sample. The details of the MR analysis will be published elsewhere.

In passing, let us briefly mention our analysis to see if any scaling is applicable to the MR data. Firstly, we found that the classical Kohler’s rule (∆ρ/ρ~(H/ρ)<sup>2</sup>) is strongly violated, as in other cuprates. We also found that the “modified Kohler’s rule” (∆ρ/ρ~(cot θ<sub>H</sub>)<sup>−2</sup>) is not very well applicable to our data; this is different from the results for LSCO and YBCO and might be related to the fact that cot θ<sub>H</sub> does not behave as T<sup>2</sup> except for the x=0.66 sample. The details of the MR analysis will be published elsewhere.

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