Orbital Magnetoresistance in the La$_{2-x}$Sr$_x$CuO$_4$ System

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Abstract

Measurements of resistivity, Hall effect, and magnetoresistance have been made on seven c-axis oriented thin-film specimens of La$_{2-x}$Sr$_x$CuO$_4$ with values of $x$ from 0.048 to 0.275, and one specimen that also contains Nd. The orbital magnetoresistance is found not to be proportional to the square of the tangent of the Hall angle except for values of $x$ near 0.15 above about 80K. For smaller values of $x$ the temperature dependence of the magnetoresistance is different, but quite similar in the various specimens, in spite of large differences in resistivity, Hall coefficient, and Hall angle.
While there is still no consensus on the origin of high-temperature superconductivity, it is generally believed that the key to further understanding is likely to be found in the anomalous properties of the normal state of these materials. Most notably, the properties seem not to be in accord with the Landau Fermi–liquid theory of conventional metals. It has been suggested that the anomalous transport properties may require two distinct scattering rates for their description. One of them, $\tau_{tr}^{-1}$, governs conductivity and photoemission, and for optimally-doped compounds varies linearly with temperature up to 1000K. The other, $\tau_{H}^{-1}$, is inferred from the Hall effect and varies as $T^2$ over a broad range of temperatures and carrier concentrations. The orbital magnetoresistance (MR) is an additional property that may be used to investigate the behavior of the scattering rates, and to test the hypothesis that there are two separate relaxation times.

In a normal metal with a single relaxation time and an anisotropic Fermi surface the weak-field MR, $\Delta \rho/\rho = [\rho(H) - \rho(0)]/\rho(0)$, is proportional to $(\omega_c \tau)^2$, where $\omega_c$ is the cyclotron frequency. If the relaxation time is the same as that which governs the Hall effect, $\Delta \rho/\rho$ is then expected to be proportional to $(\tan \Theta_H)^2$, where $\Theta_H$ is the Hall angle. In recent studies this relationship was indeed found to be followed, by Harris et al. for two samples of YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) and one of La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) down to about 100K, and by Hussey et al. in overdoped Tl$_2$Ba$_2$CuO$_6$.

In this letter we report measurements on a series of specimens of the LSCO system which show that the expected relationship between the magnetoresistance and the Hall effect is followed over only a rather limited range of temperature and composition, namely above about 80 K and most closely for the optimally doped compound, with departures that grow as the metal–insulator transition is approached. Although the ratio $(\Delta \rho/\rho)/(\tan \Theta_H)^2$ is generally not constant, as would be expected if the MR and the Hall effect are governed by the same relaxation time, the functional form of the temperature dependence of this ratio is similar for all of the underdoped specimens in our study.

The specimens are c-axis oriented films, about 5000 Å thick, made by pulsed laser deposition on LaSrAlO$_3$ substrates. The specimen with $x = 0.105$ was, in addition,
annealed in high-pressure oxygen, leading to a higher value of $T_c$. The compositions are nominal, as determined from the weights of the materials used for the targets, but previous work has shown them to be close to the film compositions. The films were patterned by photolithography, with arms for the longitudinal and transverse voltage measurements. Silver pads were evaporated on them and gold wires attached with silver epoxy or indium solder.

The measurements were made in a cryostat with an 8 T superconducting magnet. The temperature was measured with a *cernox* thermometer and stabilized to about 3 parts in $10^6$ with a computer-controlled feedback loop. The magnetoresistance of the sensor was measured separately (see also Ref. [12]), and in any case does not affect the orbital magnetoresistance, which was assumed to be the difference between the measurements made in the transverse (field perpendicular to the current and parallel to the $c$–axis) and the longitudinal (field parallel to the current) orientations.

The values of $T_c$ are, in general, somewhat lower than those of bulk single crystals of the same composition, and the resistivities somewhat higher. Both parameters depend sensitively not only on the metal concentration, but also on disorder and oxygen content, which are more difficult to control. The metal–insulator transition occurs at about $x = 0.05$, and in its vicinity small changes in composition correspond to large changes in $T_c$ and $\rho$. In addition the measurement of the resistivity depends on the thickness, which has an uncertainty of the order of 20%.

The characteristics of the specimens are shown in Table I. Specimens 1 to 7 differ in their La–Sr ratio, with values of $x$ of 0.048, 0.06, 0.105, 0.135, 0.15, 0.225, and 0.275. Specimen 8 also contains Nd (La$_{1.75}$Nd$_{0.15}$Sr$_{0.1}$CuO$_4$), with a value of $T_c$ close to that of specimen 2 ($x = 0.06$), but with a resistivity larger by a factor of about three. Its resistivity has a much more pronounced maximum near $T_c$, as can be seen on Fig. [1], which shows the in–plane resistivity, $\rho$, as a function of temperature for all specimens.

Fig. 2 shows the cotangent of the Hall angle, $\cot \Theta_H = (\omega_e \tau_H)^{-1}$, as a function of $T^2$. The measured points fall on straight lines ($bT^2 + c$) over a substantial temperature range.
for the specimens with $x \leq 0.15$, as expected for a relaxation time proportional to $T^{-2}$. For the underdoped specimens there is an upturn at low $T$, in the region where $\rho(T)$ also departs from linearity, as observed previously. [13,14] The highly overdoped specimen with $x = 0.275$ exhibits substantial curvature on this graph, becoming proportional to $T^{1.4}$ in the high–$T$ region, which is also the temperature dependence of the resistivity for this specimen. This behavior is in keeping with the approach to the normal–metal regime, with a single scattering time, and adherence to Kohler’s rule, $\Delta \rho/\rho \propto (H/\rho)^2$, as $x$ increases to the strongly overdoped regime. [13] Weak curvature is also apparent for the specimen with $x = 0.225$. In the opposite regime, for the specimen with $x = 0.048$, there is a sharp drop as $T$ goes to zero, reflecting the divergence of the Hall coefficient at the metal–insulator transition.

The magnetoresistance is positive and proportional to $H^2$ from approximately 40K to 300K. The field dependences of the resistances were fitted to parabolas and normalized to 1 tesla. The transverse MR increases as $x$ increases, while the longitudinal MR, which is generally much smaller, decreases. We attribute the longitudinal MR to isotropic spin scattering, which may be expected to increase as the antiferromagnetic insulating state is approached, consistent with our results.

Fig. 3 shows the orbital magnetoresistance, i.e. the difference between the transverse and the longitudinal MR, as a function of temperature for all specimens, with the curves for the underdoped specimens and the one containing neodymium on the lower graph, and the curves for the optimally doped ($x = 0.15$) and overdoped specimens on the upper graph. The figure exhibits several striking and unexpected features. One is that the magnitude of the MR does not vary greatly over the whole range of specimens, especially in the high–$T$ region. Another is that the curves for the underdoped specimens with $x \leq 0.105$ are concave over the whole measurement range. This is the opposite curvature from that expected if the MR is proportional to $\tau_H^2$, i.e. to $(bT^2 + c)^{-2}$. The curves for the specimens with $x = 0.135$ and 0.15 show points of inflection, and those for the overdoped ones are convex, except at the lowest temperatures.
In Ref. [7] deviations below 100K were apparent for all three of their specimens, and were ascribed to superconducting fluctuations. This was not unreasonable for the two YBCO specimens with values of $T_c$ of 90K and 60K, and only mildly surprising for the LSCO specimen with its $T_c$ of 38K. Since, however, the data do not scale with $(T–T_c)/T_c$, and the specimen with $x = 0.048$ shows no signs of superconductivity in the range of the measurements, it is evident that the upturn at the low–T end of the curves is not caused by superconducting fluctuations, except, perhaps, to a minor extent.

A particularly interesting case is that of the specimen with strontium content $x = 0.1$ and 0.15 neodymium. Its magnetoresistance is almost indistinguishable from that of the specimen with $x = 0.06$, which has almost the same transition temperature. At the same time the cotangent of its Hall angle places it close to the optimally doped specimen, except for the fact that its upturn on Fig. 2 is larger than that of any other specimen. Its resistivity, the resistance peak at low T, and Hall coefficient are all larger than those of any other specimen. On the other hand $R(T)$ is quite straight above the peak, unlike its underdoped neighbors on Fig. 1. The fact that the behavior of these quantities does not seem to be correlated with those of the specimens without Nd emphasizes the earlier conclusion that not only the resistivity, but also the Hall effect seem to be quite decoupled from the magnetoresistance. Its carrier concentration and the amount of disorder seem to put this specimen in a quite different category from the others, and a more extended set of measurements with this and other impurities will be necessary to allow the effects of these parameters to be assessed and separated.

To emphasize the unexpected relation between Hall effect and MR we show on Fig. 4 the orbital MR divided by the square of the Hall angle, as a function of T. It is apparent that there is no proportionality between the magnetoresistance and the square of the Hall angle, except for the high–temperature part of the curve for the optimally–doped specimen and, approximately, for $x = 0.225$. The graph also shows that the temperature dependences for all of the underdoped specimens are similar to each other, with a minimum at about 150K.

The point of inflection that was mentioned earlier is most readily apparent in the MR
curves for the specimens with values of $x$ of 0.15 and 0.135. It seems also to be present, even if less distinctly, for $x = 0.225$ and $x = 0.275$, moving to progressively lower T as $x$ increases. The fact that no point of inflection is seen in the curves for smaller $x$ may be because it has then moved to temperatures beyond those of this experiment. The temperature dependence of the inflection point leads us to suggest the possibility that it may be correlated with the opening of a pseudogap in the normal state. \[2,16,17\]

We now consider some earlier measurements, which are, in general, less precise than those of Ref. \[7\] and those that we present here. Lacerda et al. \[18\] measured the magnetoresistance of a single crystal with $x = 0.075$. They state that the magnetoresistance is proportional to $T^{-2}$, but their result is, in fact, in qualitative agreement with ours, considering the larger uncertainty of their measurement. Preyer et al. \[19\] measured single crystals with $x = 0.02, 0.06$, and 0.1. They find an isotropic negative magnetoresistance, and we can only suspect that their specimens contained unknown magnetic impurities subject to strong spin scattering.

A study by Kimura et al. \[15\] describes measurements on a series of samples that partially overlap those described here. For their sample with $x = 0.09$ they conclude that the magnetoresistance is determined entirely by superconducting fluctuations up to 100K. Our work conflicts with this conclusion since the magnetoresistance does not scale with $(T-T_c)/T_c$, as we stated earlier. A detailed comparison is made difficult since they do not show graphs of $\Delta \rho/\rho$ as a function of T, but there are indications of differences from our results. Refs. \[7\] and \[15\] emphasize the departures from Kohler’s rule, and in this respect our results agree with theirs.

To summarize, we see that the most interesting and novel aspect of our results is the description of the MR in the underdoped region ($x \leq 0.135$). Here the temperature dependence of the MR is similar for all of our specimens, even though there are large differences in resistivity, Hall coefficient, and Hall angle. The temperature dependence of the ratio of the orbital magnetoresistance to the square of the Hall angle is also similar in these specimens (although with different magnitude), with a minimum at about 150K. For the optimally
doped specimen ($x = 0.15$) and the next overdoped specimen ($x = 0.225$) the proportionality between $\Delta \rho/\rho$ and $\Theta^2_H$ is followed, at least approximately, and for even higher values of $x$ normal–metal behavior is recovered. The point of inflection in the temperature dependence of the MR may be a signal of the opening of a pseudogap.

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FIG. 1. The resistivity of all samples as a function of temperature.
FIG. 2. The cotangent of the Hall angle as a function of $T^2$. The straight-line portions were fitted to the relation $bT^2 + c$. The coefficients $b$ and $c$ are given in Table 1.
FIG. 3. The orbital magnetoresistance as a function of temperature, for all specimens, normalized to 1 tesla. The dotted lines follow the equation $a/(bT^2 + c)^2$, with the scaling constant, $a$, chosen to fit the high-temperature data, on the upper graph for $x = 0.15$ and on the lower graph for $x = 0.105$. 
FIG. 4. The ratio of the magnetoresistance to the square of the Hall angle for all specimens, normalized to 1 tesla.
TABLE I. Characteristics of the specimens, \( \text{La}_{2-x-y}\text{Sr}_x\text{Nd}_y\text{CuO}_4 \).

The coefficients \( b \) and \( c \) are obtained by fitting the relation \( bT^2 + c \) to the straight-line portions of the Hall effect data on Fig. 2.

| sample | \( x \)  | \( y \)  | \( T_c \) (K) | \( \rho_{300} \) (mOhm cm) | \( b \)  | \( c \)  |
|--------|--------|--------|--------------|----------------|--------|--------|
| 1      | 0.048  | 0      | N/A          | 3.9            | 0.0075 | 415    |
| 2      | 0.06   | 0      | 10.2         | 3.4            | .031   | 1050   |
| 3      | 0.105  | 0      | 31           | 1.7            | .075   | 2250   |
| 4      | 0.135  | 0      | 27           | 2.3            | .09    | 1825   |
| 5      | 0.15   | 0      | 29.5         | 1              | .095   | 1455   |
| 6      | 0.225  | 0      | 16.5         | 0.67           | N/A    | N/A    |
| 7      | 0.275  | 0      | 10.7         | 0.345          | N/A    | N/A    |
| 8      | 0.1    | 0.15   | 9.6          | 10.6           | .103   | 3060   |