Two lifetimes and the pseudogap in the orbital magnetoresistance of Zn–substituted La$_{1.85}$Sr$_{0.15}$CuO$_4$

A. Malinowski $^{1,2}$, A. Krickser $^1$, Marta Z. Cieplak $^{1,2}$, S. Guha $^1$, K. Karpinska $^2$, M. Berkowski $^2$, and P. Lindenfeld $^1$

$^1$ Department of Physics and Astronomy, Rutgers University, Piscataway, NJ 08854, USA

$^2$ Institute of Physics, Polish Academy of Sciences, 02 668 Warsaw, Poland

The effect of zinc doping on the anomalous temperature dependence of the magnetoresistance and the Hall effect in the normal state was studied in a series of La$_{1.85}$Sr$_{0.15}$Cu$_{1-y}$Zn$_y$O$_4$ films, with values of $y$ between zero and 0.12. The orbital magnetoresistance at high temperatures is found to be proportional to the square of the tangent of the Hall angle, as predicted by the model of two relaxation times, for all Zn–doped specimens, including nonsuperconducting films. The proportionality constant is equal to $13.7 \pm 0.5$ independent of doping. This is very different from the behavior observed in underdoped La$_{2-x}$Sr$_x$CuO$_4$ films where a decrease of $x$ destroys the proportionality. In addition, the behavior of the orbital magnetoresistance at low temperatures is found to be different depending on whether $x$ is changed or $y$. We suggest that these differences reflect a different evolution of the pseudogap in the two cases.

74.20.Mn, 74.25.-q, 74.72.Dn, 74.25.Fy, 74.76.Bz

The anomalous normal–state transport properties of cuprate superconductors represent a major challenge on the way toward the understanding of the physics of these materials. The assumption that there are two different relaxation times is an attempt to explain anomalies observed in the resistivity, Hall effect and magnetoresistance. It predicts a simple relation between the orbital magnetoresistance and the Hall angle ($\Delta \rho/\rho \propto \tan^2 \Theta_H$), which is indeed observed, at least at high temperatures in optimally doped cuprates. One explanation relates the behavior of the Hall coefficient to the opening of the pseudogap in the normal state. Recent photoemission studies even point to the possibility of two different pseudogaps, a low–energy pseudogap related to the evolution of the Fermi surface into discontinuous Fermi discs in the underdoped cuprates, and a high–energy pseudogap, possibly related to the magnetic interactions.

Recently we described measurements of the orbital magnetoresistance (OMR) and the Hall effect on a wide range of La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) films, from $x = 0.048$ with no superconductivity down to 4 K, through the superconducting range, to $x = 0.275$ with properties approaching those of a normal metal. We found that the predicted relation between the Hall angle and the magnetoresistance is not followed except in optimally doped films at temperatures above 100K. At lower temperatures there is a point of inflection in the curve of the OMR as a function of $T$, below which the OMR increases rapidly. The large positive OMR observed below the inflection point survives in the nonsuperconducting specimens, indicating that it cannot be attributed solely to superconducting fluctuations as originally suggested. The point of inflection is seen to move to higher temperatures as $x$ decreases in the underdoped specimens, and we have suggested that this feature may be related to the opening of a pseudogap as the metal–insulator transition is approached.

To reach a fuller understanding we have made measurements of OMR and Hall effect on films of La$_{1.85}$Sr$_{0.15}$Cu$_{1-y}$Zn$_y$O$_4$ with $y$ from zero to 0.12. Superconductivity is absent when $y$ is greater than 0.055. We find that the change of $y$ gives rise to a distinctly different evolution of the OMR than a change of $x$. In particular, the inflection point on the OMR curve does not shift with $y$, consistent with a pseudogap–opening that is unaffected by a change of $y$. Moreover, the proportionality between the OMR and $\tan^2 \Theta_H$ is followed for all specimens, including nonsuperconducting films, with a proportionality constant which does not change with $y$ and remains equal to the value reported previously for zinc–free LSCO. This unexpected result is easily explained by the models which use two relaxation times, but is much more difficult to understand on the basis of more conventional Fermi–liquid theories which assume anisotropic relaxation rates.

The $c$–axis oriented films, about 6000 Å thick, were grown by pulsed laser deposition on LaSrAlO$_4$ substrates. The values of $y$ are those of the targets, but have been shown to be the same as in the films. The specimens for the present study were selected for their small residual resistivity. Their dependence of the in–plane resistivity on temperature is shown in Fig. 1(a). The inset shows the room–temperature resistivity, $\rho_{RT}$, as a function of $y$. It exceeds by about 30% that of similar single crystals. However, while $y$ was no greater than 0.04 in the single crystals, we are able to reach values three times as high without any deterioration of the film quality.

The films were patterned by photolithography and the wires soldered with indium to evaporated silver pads. Standard six–probe geometry was used to measure Hall voltage and magnetoresistance simultaneously. The measurements were made in magnetic fields up to 8 T, in...
longitudinal fields (parallel to the $ab$–plane) and in transverse fields (perpendicular to the $ab$–plane and to the current), with $T$ between 25 K and 300 K. The temperature was stabilized to about 3 ppm, as described previously.

The Hall voltage is a linear function of field for all fields. Fig. 1(b) shows the Hall coefficient, $R_H$, as a function of $T$. It is seen that the increase of $y$ causes a decrease of $R_H$ without affecting the shape of $R_H(T)$. The change in $R_H$ is about an order of magnitude less than in LSCO when $x$ is decreased from optimal ($x = 0.15$) toward the strongly underdoped regime ($x = 0.048$). The decrease of $R_H$ confirms the results previously observed in ceramic specimens up to $y = 0.03$. Note that a decrease of $x$ causes an increase of $R_H$ while an increase in $y$ causes an opposite trend. The change in $y$ does not lead to a superconductor–insulator transition, but rather to a metallic nonsuperconducting phase. The fact that the shape of $R_H(T)$ remains unaffected by the variation of $y$ is different from what happens with overdoping of LSCO, which also leads to a metallic phase, but destroys the anomalous $T$–dependence of $R_H$.

Fig. 2 shows that the data for the Hall angle can be described by $\cot \Theta_H = bT^2 + c$ from 25 K to 200 K. The variation of the coefficients $b$ and $c$ is shown in the inset. The coefficient $c$ increases linearly with $y$ for all superconducting films at a rate equal to $38 \pm 4$ per at.% of Zn (and faster in nonsuperconducting films). This is about three times as fast as in zinc–substituted YBa$_2$Cu$_3$O$_{7-\delta}$ [15]. The parameter $b$ is not constant, as suggested for YBa$_2$Cu$_3$O$_{7-\delta}$ [15], but increases with $y$.

The inset to Fig. 3 shows a typical example of the dependence of the magnetoresistance on temperature. In all specimens the transverse magnetoresistance (TMR) is positive down to 25 K, and it is always larger than the longitudinal magnetoresistance (LMR). The LMR is negative and very small above 200 K, approaching the experimental resolution of the measurement. At lower $T$ the LMR becomes positive, and larger when $x$ decreases, or when $y$ increases. In nonsuperconducting specimens with small $x$ or large $y$ the LMR becomes negative and large below 25 K, consistent with the expectation that the magnetic interactions, and the isotropic spin scattering, which is presumably responsible for the LMR, then play an increasingly important role.

To obtain the OMR we subtract the longitudinal component from the transverse magnetoresistance. The temperature dependence of the OMR is shown in Fig. 3. A dramatic suppression of the positive OMR occurs at low temperatures as $y$ increases, until it becomes negative in nonsuperconducting specimens. This is very different from the behavior of the OMR in LSCO, where a large positive OMR survives in nonsuperconducting films. This difference supports our previous conclusion that superconducting fluctuations are not solely responsible for the positive OMR observed at low temperatures. Since superconducting fluctuations are expected to exist in the vicinity of $T_c$ in underdoped and in zinc–doped...
LSCO, they would lead to the same behavior in both types of specimens. Evidently this is not the case.

FIG. 3. The orbital magnetoresistance at 8 T as a function of $T$, for all zinc–doped specimens. Inset: The temperature dependence of the transverse and longitudinal magnetoresistance at 8 T for the film with $y = 0.035$. All lines are guides to the eye.

Fig. 4 shows the OMR on a logarithmic scale. It may be seen that the point of inflection, which is at about 70 K in the film with $y = 0$, does not change its position along the $T$–axis with increasing $y$, while with decreasing $x$ the point of inflection moves to higher temperatures. We suggest that the fact that the shift is not observed in the zinc–doped films indicates that the temperature at which the pseudogap opens is not affected by the change of $y$. This may be understood if one assumes that the zinc doping affects the pseudogap behavior only locally, in the immediate vicinity of the impurity, but not in the bulk of the specimen. Thus, while the doping affects the scattering in the bulk of the specimen as seen by the fact that both the Hall angle and the OMR above the point of inflection change with $y$, the temperature of the pseudogap opening does not change. A similar suggestion was made in a study of the thermopower in zinc–doped YBa$_2$Cu$_3$O$_{7-\delta}$ and YBa$_2$Cu$_3$O$_8$ [10].

Further insight into the nature of the scattering comes from testing the relation between the OMR and the square of the tangent of the Hall angle. We find that this relation is followed for all zinc–doped specimens at temperatures above the inflection point. Examples of this dependence are shown in the inset to Fig. 5 for three films. The dotted lines are fits to the equation $a/(bT^2 + c)^2$. A comparison of the experimental values of the OMR and $\tan^2 \Theta_H$, measured at temperatures above the inflection point for all of the zinc–doped films, is shown on a log–log plot in Fig. 5. With the exception of data for $y = 0.12$, which are close to the limit of resolution in our experiment, the data fall on straight lines which have approximately the same slope. Small parallel shifts between them probably result from experimental uncertainty of the sample sizes. Excluding the data for $y = 0.12$, we can fit the data with a straight line with slope $0.94 \pm 0.06$. The proportionality constant $a$, averaged over all data, is equal to $13.7 \pm 0.5$, in excellent agreement with the value 13.6 reported for LSCO with $x = 0.17$ by Harris et al. [3].

The observation that the proportionality constant $a$ is unaffected by doping puts strong constraints on the theoretical models which attempt to explain the anomalous properties of the normal state in cuprates. These models may be divided into two classes. Those in one class, the Fermi–liquid models, are based on the assumption that some strong, unusual anisotropy of the relaxation rates around the Fermi surface leads to the anomalies [11]. Although details of these models vary, it would be expected that the ratio of the OMR to $\tan^2 \Theta_H$ would depend on temperature and doping so that our observation would require some fortuitous cancellation. The models in the second class assume the existence of two different relaxation rates at all points of the Fermi surface [11, 12]. It is a fundamental property of these models that the ratio of the OMR to $\tan^2 \Theta_H$ is constant, and should not be affected by doping. These models thus ap-

![Figure 3](image1.png)

![Figure 4](image2.png)
pear to be favored by our results. Finally we note that high-magnetic-field studies of the magnetoresistance in \( \mathrm{Tb}_2\mathrm{Ba}_2\mathrm{CuO}_{6+\delta} \) also favor the two lifetime models [2]. Their microscopic understanding remains, however, elusive. We conclude that the metallic phase created by zinc doping retains the anomalous characteristics that are observed at high temperatures in optimally doped LSCO, in both the OMR and the Hall effect, together with the relationship between them. We suggest that the striking contrast between this result and our previous observation of the dissapearance of the proportionality between OMR and Hall angle in underdoped LSCO [7] is related to the opening of a pseudogap. Apparently the opening of the pseudogap destroys this characteristic feature of the anomalous normal state.

We would like to thank M. Gershenson for his cooperation and sharing of laboratory facilities, and Piers Coleman and Andrew Millis for helpful discussions. We also thank Richard Newrock and the Physics Department of the University of Cincinnati for help with the construction of the target chamber. This work was supported by the Polish Committee for Scientific Research, KBN, under grant 2 P03B 09414, by the Naval Research Laboratory, and by the Rutgers Research Council.

---

**FIG. 5.** Log–log plot of the orbital magnetoresistance versus \( \tan^2 \Theta_H \), measured at temperatures above the inflection point in films with various values of \( y \). Inset: The orbital magnetoresistance at 8 T as a function of temperature for three films with \( y = 0, 0.035, \) and 0.08. The dotted lines follow the equation \( a/(bT^2 + c)^2 \).