Magnetoresistance in the normal state of $La_{1.925}Sr_{0.075}CuO_{4+\delta}$

A. Lacerda,* J. P. Rodriguez,† M. F. Hundley, Z. Fisk, P. C. Canfield,‡ and J. D. Thompson
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

S. W. Cheong
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
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The in-plane magnetoresistance of a high-quality single crystal of $La_{1.925}Sr_{0.075}CuO_{4+\delta}$ has been measured in both the high-symmetry transverse geometry and in the longitudinal geometry. In both orientations, the magnetoresistance is positive and shows conventional weak-field behavior. The measured longitudinal magnetoresistance, however, is found to be almost an order of magnitude smaller than the measured transverse magnetoresistance. A semiphenomenological theory based on anisotropic scattering from hypothesized hole-pocket Fermi surfaces is introduced, which can account for the latter positive effect, as well as for known Hall-effect measurements. We predict that, in the limit corresponding to perfectly coherent in-plane hole motion along (π,π), there should be no saturation effect in the high-symmetry transverse magnetoresistance.

I. INTRODUCTION

It is widely suspected that the novel transport properties observed in the normal state of the layered cuprate high-temperature superconductors reflect the essential physics responsible for the phenomena of high-temperature superconductivity itself.[1-3] In particular, the T-linear in-plane resistance characteristic of these materials appears to be most prominent at compositions for which the superconducting critical temperature T_c is optimized.[4] Although various theoretical pictures based on antiferromagnetic spin fluctuations, chiral spin fluctuations, the marginal Fermi-liquid hypothesis, and quasinested Fermi surfaces have been proposed to account for the peculiar linear temperature dependence alone (see Ref. 2), no overall theoretical understanding of the charge and the spin dynamics in these interesting systems yet exists.

In order to make a step towards elucidating the nature of the electronic dynamics of the copper-oxygen (Cu-O) planes common to the oxide superconductors, which are believed to lie at the heart of the phenomenon, we have studied the in-plane magnetotransport properties of the underdoped high-temperature superconductor $La_{1.925}Sr_{0.075}SuO_{4+\delta}$ in its normal state. This material has a superconducting transition temperature of $T_c \cong 23$ K, with an a-b axis normal-state resistance that is T-linear at high temperatures and that shows a characteristic "semiconducting" upturn just above T_c.[2] In magnetic field, H, of up to 10 T we find a weak yet positive in-plane magnetoresistance for both the transverse geometry, with field along the c axis, and for the longitudinal geometry, with field along the in-plane flow of current. The longitudinal effect is smaller than the transverse effect by almost an order of magnitude at low temperatures ($T<50$ K). Quantitatively, we find that the magnetoresistance $\Delta\rho(H)/\rho(0)$ scales with $[H/\rho(0)]^2$ in the high-temperature regime, thus following Kohler's rule.[5] This suggests a transport relaxation time scale $\tau_{tr} \sim \hbar/k_B T$ that is consistent with the T-linear zero-field resistivity, $\rho(0)$, exhibited at high temperatures. The latter functional dependence with magnetic field also implies that the effect we measure lies in the weak-field regime, $\omega_c\tau_{tr} \ll 1$, where ω_c here denotes the cyclotron frequency. In general, we find that our results are consistent with prior magnetotransport studies of $Bi_2Sr_2CuO_6$ at similar temperature ranges.[6] However, in previous work, Preyer *et al.* reported a negative isotropic magnetoresistance in underdoped compositions of lanthanum-based copper oxides at comparable temperatures,[7] in conflict with our observations. At present, we do not understand this discrepancy.

To account for our experimental results, we introduce a semiclassical picture based on the hypothesized existence of anisotropic scattering[5] from two-dimensional (2D) Fermi-surface hole "pockets". Such Fermi surfaces are expected to appear, for example, in strongly interacting 2D electron systems near an antiferromagnetic instability,[8] which is thought to accurately model the charge-spin dynamics of the Cu-O planes in the oxide superconductors.[3] Inelastic neutron scattering measurements on the same material, in fact, show evidence for proximity to such an instability.[9] The principal virtues of the hole "pockets" approach are that it predicts a hole-type Hall effect consistent with a large body of experimental data,[1] and that it predicts a *positive* magnetoresistance effect in agreement with our measurements. In particular, as a proof of principle, we show that a modest positive transverse effect is expected in the high-field limit for the case where the magnetic field is aligned along the c axis. We hope to address the potentially more relevant calculation of the weak-field magnetoresistance within this picture in a future publication. Last, it is important to remark that a more microscopic approach[10] based on the scattering of

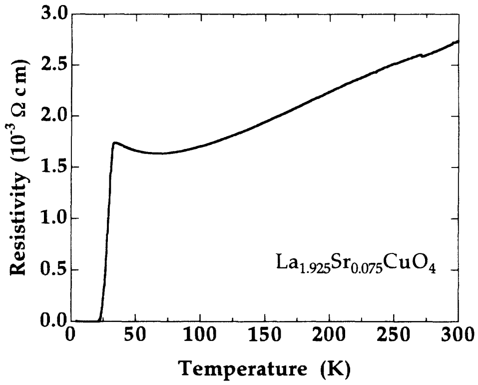

FIG. 1. Shown is the *a-b*-axis resistivity profile for $La_{1.925}Sr_{0.075}CuO_{4+\delta}$ as a function of temperature.

strongly interacting 2D electrons from so-called chiral spin fluctuations predicts a negative magnetoresistance that is strongly anisotropic.

II. EXPERIMENTAL RESULTS

We have measured the in-plane resistivity and the in-plane magnetoresistance of a high-quality single crystal of $La_{1.925}Sr_{0.075}CuO_{4+\delta}$; i.e., the current flow I remained always in the *a-b* axis plane. Both the resistance and the magnetoresistance have been measured using the conventional four-probe technique with a low-frequency LR-400 resistance bridge, in a temperature range between 4 K$<T<$310 K, and in magnetic fields of up to 10 T. When measuring the magnetoresistance, special care was taken to ensure the proper regulation of temperature in field. The latter is particularly important in present case, where the measured temperature dependence of the resistance at zero field is strong above 100 K (see Fig. 1). The temperature regulation was checked by sweeping the magnetic field at different rates (e.g., from 0.0 to 10.0 T in a time range spanning from 25 min to 3 h) and by use of capacitor-based sensors. Contact resistances of approximately 1 Ω were obtained by using silver-paint pads during the annealing process. The in-plane resistivity in the absence of magnetic field is shown in Fig. 1. Note that a T-linear dependence for the resistivity characteristic of the normal state of oxide superconductors is present over a wide range at high temperature. The small upturn in the resistivity just above $T_c \cong 23$ K we believe is probably a localization effect due to slight underoxygenation in our sample.

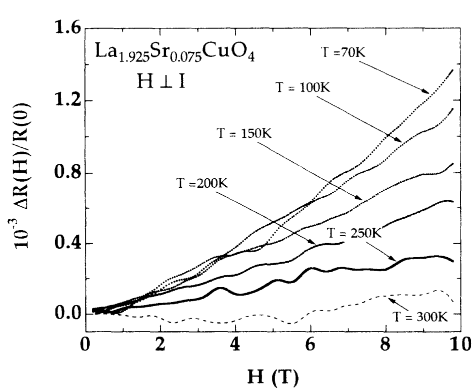

FIG. 2. High-symmetry transverse magnetoresistance, with the field along the c axis and the current flow in the ab plane, as a function of magnetic field. Notice the presence of wiggles in the data at the higher temperatures.

The central result that we have obtained in the present study of the magnetotransport properties of $La_{1.925}Sr_{0.075}CuO_{4+\delta}$ is that the in-plane magnetoresistance is generally positive in a temperature range from 23

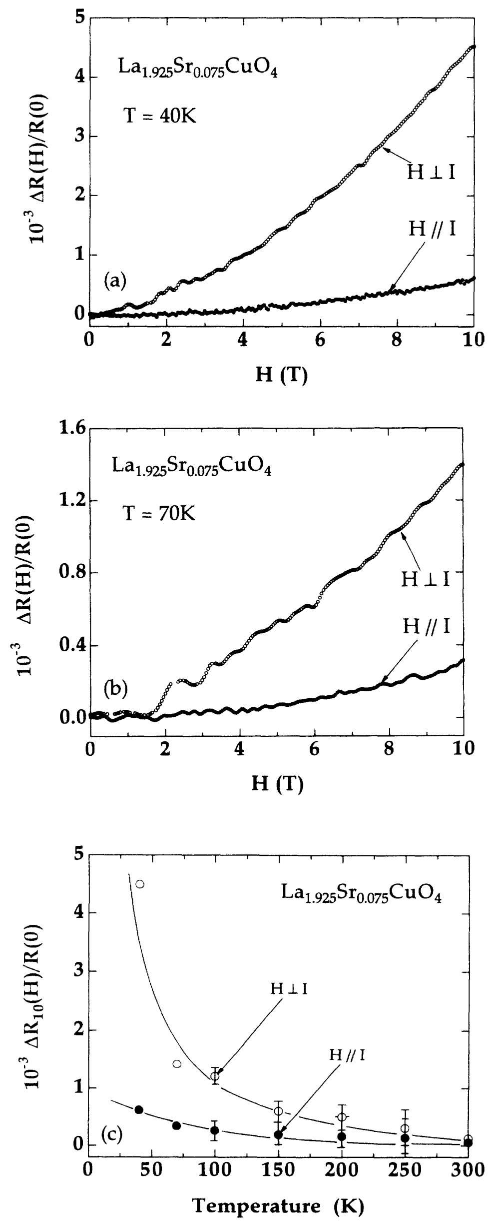

FIG. 3. Magnetoresistance as a function of magnetic field at (a) T=40 K and (b) T=70 K. Also shown (c) is the magetoresistance at 10 T as a function of temperature. In all cases, the magnetic field for transverse magetoresistance is along the c axis.

to 200 K, and in magnetic fields of up to 10 T, as shown in Figs. 2 and 3. Notice that we find no evidence for saturation of the magnetoresistance in the range of fields studied here. Also, as is displayed by Fig. 3, the longitudinal magnetoresistance ($H\|I$) is generally weaker than the high-symmetry transverse magnetoresistance ($H\|c$ axis) by almost an order of magnitude at low temperatures. Note, however, that the errors in the longitudinal and transverse magnetoresistances are considerable for temperatures above 150 K [see Fig. 3(c)]. We also see that both effects decrease with increasing temperature, that the anisotropy decreases with increasing temperature, and that both longitudinal and transverse magnetoresistances seem to show a conventional quadratic dependence with the applied magnetic field H, which is characteristic of the weak-field limit, $\omega_c\tau_{tr} \ll 1$.[5]

Given the temperature dependence of the zero-field resistivity (see Fig. 1), the latter behavior suggests that the magnetoresistance scales as $[H/\rho(0)]^2$, *à la* Kohler's rule.[5] In Fig. 4, we have replotted the transverse magnetoresistance data in this fashion. Notice in Fig. 4(b) that at high temperatures, where $\rho(0) \propto T$, the different curves collapse onto each other, thereby validating Kohler's rule. At lower temperature, however, although the dependence with $[H/\rho(0)]^2$ remains linear, the slope differs [see Fig. 4(a)]. This could be an artifact of the possible nonintrinsic nature of the zero-field resistivity at such temperatures. We may therefore summarize our experimental results as follows: (a) both the high-symmetry transverse and the longitudinal in-plane magnetoresistance in $La_{1.925}Sr_{0.075}CuO_{4+\delta}$ are positive, with $\Delta\rho_{\|}(H)/\rho(0) < \Delta\rho_{\perp}(H)/\rho(0)$; (b) the magnetoresistance scales approximately as

$$\frac{\Delta\rho(H)}{\rho(0)} \propto (H/T)^2 , \tag{1}$$

in the high-temperature regime where the zero-field resistivity is T-linear. We therefore conclude that all of the magnetotransport phenomena which we have observed lie in the weak-field regime.[5]

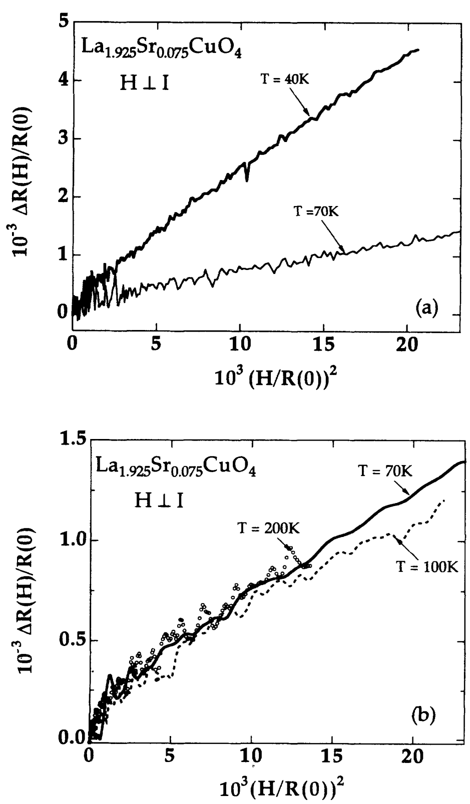

FIG. 4. Low (a) and high (b) temperature transverse magnetoresistance ($H\|c$ axis) as a function of $[H/\rho(0)]^2$, where $\rho(0)$ denotes the zero-field resistivity.

III. MODEL

The primary observation reported here of a positive in-plane magnetoresistance in the normal state of the underdoped high-temperature superconductor, $La_{1.925}Sr_{0.075}CuO_{4+\delta}$, strongly suggests that a conventional semiclassical description of the magnetotransport in this system is appropriate.[5] For example, more exotic microscopic calculations of the transverse magnetoresistance in certain strongly interacting 2D Fermi systems intended to model the Cu-O planes in these systems find a negative effect.[10] The latter result is ultimately due to the suppression of chiral spin-fluctuation scattering by the application of a magnetic field, and it is therefore intrinsically quantum mechanical in nature. In addition to the conventional aspect of the magnetotransport properties reported here, the bulk of the reported normal state transport measurements on the oxide superconductors indicate that the charge carriers are holes. For example, the Hall constant in these systems is positive in the case of fields aligned along the c axis, and it scales roughly as the inverse hole concentration.[1] In view of these considerations, we propose to base the theoretical description of our magnetotransport measurements on the hypothesis that the normal state of $La_{1.925}Sr_{0.075}CuO_{4+\delta}$ has a 2D Fermi surface consisting of hole pockets centered at the antiferromagnetic points (π,π). Such Fermi surfaces (see Fig. 5) occur naturally in the study of doped 2D antiferromagnets in the vicinity of the Mott transition[8] and they are consistent with the observation of nearly antiferromagnetic (incommensurate) spin correlations in this material.[9] Note that although there is evidence for the existence of a large 2D electron Fermi surface in the optimally doped compositions of the oxide superconductors,[11] it is quite possible that such a large surface collapses into the aforementioned hole pockets at the underdoped composition considered here. As a proof of principle, we show below that anisotropic quasielastic scattering from such hole pockets gives rise to a positive inplane magnetoresistance for the high-field limit.

Consider the high-symmetry transverse geometry for magnetoresistance in the oxide superconductors, with magnetic field oriented along the c axis, and with the current flowing in the a-b plane. It is generally expected that the hole pockets in doped 2D antiferromagnets are elliptical in shape (see Fig. 5),with the minor axis along (π,π).[8] The latter mass anisotropy simply reflects the tendency for coherent hole motion along (π,π). Given

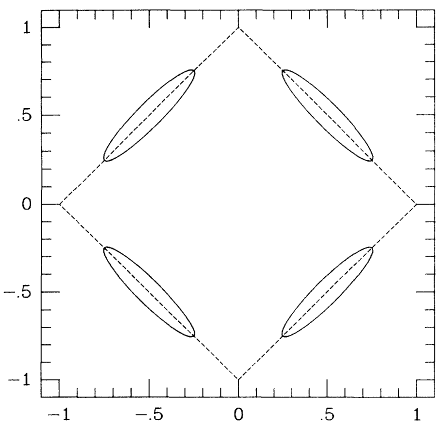

FIG. 5. Shown is the Fermi surface comprised of elliptical hole pockets centered at the anti-ferromagnetic points (π,π). The linear momentum scale is measured in units of π/a, where a denotes the relevant in-plane lattice constant. The enclosed area corresponds to the present hole concentration of $x=0.075$, while the mass anisotropy is given by $m_x/m_y=5.25$, which is close to that obtained in Ref. 8 for similar hole concentrations.

this to be the case, we parametrize the energy spectrum of the quasihole excitations by the parabolic band

$$\varepsilon(\mathbf{k})=\frac{\hbar^2k_x^2}{2m_x}+\frac{\hbar^2k_y^2}{2m_y}\ , \tag{2}$$

where $\mathbf{k}$ is the quasihole momentum measured from the center of the pocket, with k_y denoting its projection onto the minor axis (passing through the center of the pocket and the zone center), and with k_x denoting the remaining orthogonal component. Above, m_x and m_y represent the respective masses. The tendency towards coherent hole motion along (π,π), therefore, implies that $m_y<m_x$. For the sake of simplifying subsequent calculations, we work with the rescaled momenta

$$k_x'=\left[\frac{m}{m_x}\right]^{1/2}k_x=\left[\frac{m_y}{m_x}\right]^{1/4}k_x\ , \tag{3a}$$

$$k_y'=\left[\frac{m}{m_y}\right]^{1/2}k_y=\left[\frac{m_x}{m_y}\right]^{1/4}k_y\ , \tag{3b}$$

where

$$m=(m_xm_y)^{1/2} \tag{4}$$

is the cyclotron mass. Then in terms of such rescaled momentum variables, the energy spectrum of quasihole excitations (2) may be simply expressed as $\varepsilon(\mathbf{k}')=k'^2/2m$. The Fermi surface in this transformed momentum space is therefore circular, but the area that it contains remains invariant. Suppose now that the anisotropic hole pocket (2) induces a correspondingly anisotropic quasielastic scattering rate for charge transport. If so, we may model such a scattering rate on the rescaled Fermi surface by a combination of an s-wave and a d-wave dependence in two dimensions;[5] i.e., as a function of the rescaled momentum $\mathbf{k}'$, we suppose that the inverse transport lifetime is given by

$$\tau_{\mathrm{tr}}^{-1}(\mathbf{k}')=\tau_0^{-1}+\tau_1^{-1}\cos2\phi'\ , \tag{5}$$

where ϕ' denotes the angle $\mathbf{k}'$ makes with the x axis ($\phi'=\pi/2$ is along the y axis). Note that the microscopic origin for the scattering process itself could be antiferromagnetic spin fluctuations or chiral spin fluctuations, which are known to result in T-linear temperature dependences for the transport rate (5) in certain instances.[2] More conventional mechanisms such as electron-phonon scattering and impurity scattering simply do not recover the correct temperature dependence for the in-plane resistance commonly observed in the normal state of the oxide superconductors.[2]

Before computing the transverse magnetoresistance, we first compute the conductivity due to such anisotropic scattering in the absence of magnetic field. After making a straightforward generalization of the calculation by Pippard for the zero-field conductivities in the case of a circular Fermi surface [see Eqs. (1.62) and (1.63) in Ref. 5], we find that the corresponding resistivities for the general case of the elliptical Fermi surface considered here are given by

$$\sigma_{xx}(0)=\frac{ne^2\tau_1}{m_x}\left[1-\left[\frac{1-r}{1+r}\right]^{1/2}\right]\ , \tag{6a}$$

$$\sigma_{yy}(0)=\frac{ne^2\tau_1}{m_y}\left[\left[\frac{1+r}{1-r}\right]^{1/2}-1\right]\ , \tag{6b}$$

where n is the density of holes in a given pocket, and where $r=\tau_0/\tau_1$ is the anisotropy parameter for in-plane quasielastic scattering. Hence, the in-plane conductivity resulting from the entire hole-pocket Fermi surface shown in Fig. 5 at zero field is given by

$$\begin{aligned}\sigma(0)&=\sigma_{xx}(0)+\sigma_{yy}(0)\\&=ne^2\tau_1\left\{m_x^{-1}\left[1-\left[\frac{1-r}{1+r}\right]^{1/2}\right]\right.\\&\qquad\left.+m_y^{-1}\left[\left[\frac{1+r}{1-r}\right]^{1/2}-1\right]\right\}\ .\end{aligned} \tag{7}$$

Given the square symmetry of our problem, this conductivity is independent of direction in the plane. As we mentioned above, if both scattering rates τ_0^{-1} and τ_1^{-1} exhibit T-linear temperature dependence as a result of the appropriate inelastic scattering mechanism, and if we assume that the masses m_x and m_y are temperature independent, then Eq. (7) indicates that the zero-field resistivity should be T-linear, in agreement with our high-temperature measurements (see Fig. 1). Within the framework of a doped antiferromagnet, it is conceivable that the latter masses remain constant throughout our present experimental range, $T<300$ K, since the relevant energy scale in such case is the antiferromagnetic exchange coupling constant, $J\sim1000$ K.

Let us now actually compute the transverse magnetoresistance in the high-field limit. Again, a direct generalization of Pippard's calculation for the effect in the case of a circular Fermi surface yields the following conductivity tensor for the general case of an elliptical Fermi surface [see Eq. (1.69) in Ref. 5]; $\sigma_{xx}(\infty)=nm_y(\tau_0^{-1}-\frac{1}{2}\tau_1^{-1})/H^2$, $\sigma_{yy}(\infty)=nm_x(\tau_0^{-1}+\frac{1}{2}\tau_1^{-1})/H^2$, and $\sigma_{xy}(\infty)=-\sigma_{yx}(\infty)=ne/H$. Note that the prefactors in these expressions for the diagonal conductivities are obtained by comparison with the isotropic case (Ref. 5) $\tau_1^{-1}=0$. Also observe that we implicitly assume here that the transport scattering rate (5) is *independent* of magnetic field. Inversion of the conductivity tensor then yields diagonal resistivities

$$\rho_{xx}(\infty)=\frac{\sigma_{yy}(\infty)}{\sigma_{xy}^2(\infty)}=\frac{m_x}{ne^2}(\tau_0^{-1}+\tfrac{1}{2}\tau_1^{-1}) , \tag{8a}$$

$$\rho_{yy}(\infty)=\frac{\sigma_{xx}(\infty)}{\sigma_{xy}^2(\infty)}=\frac{m_y}{ne^2}(\tau_0^{-1}-\tfrac{1}{2}\tau_1^{-1}) , \tag{8b}$$

for a given hole pocket. Therefore, since the entire high-field conductivity resulting from the hole pockets Fermi surface shown in Fig. 5 is the sum $\sigma(\infty)=\rho_{xx}^{-1}(\infty)+\rho_{yy}^{-1}(\infty)$, we find, after collecting the previous results, that the ratio of the high-field and zero-field resistivities is given by the expression

$$\frac{\rho(\infty)}{\rho(0)}=\frac{\sigma(0)}{\sigma(\infty)}=\frac{1-\left[\dfrac{1-r}{1+r}\right]^{1/2}+\dfrac{m_x}{m_y}\left[\left[\dfrac{1+r}{1-r}\right]^{1/2}-1\right]}{\left[\dfrac{1}{r}+\dfrac{1}{2}\right]^{-1}+\dfrac{m_x}{m_y}\left[\dfrac{1}{r}-\dfrac{1}{2}\right]^{-1}} . \tag{9}$$

Notice above that there is no magnetoresistance effect $[\rho(\infty)/\rho(0)=1]$ for isotropic scattering ($r=0$), as is generally expected.[5] Also, further inspection of the above expression reveals that the magnetoresistance effect it describes is generally positive $[\rho(\infty)/\rho(0)\geq 1]$.

In the case of circular hole pockets, $m_x=m_y$, the general expression (9) that we have obtained for the high-symmetry transverse magnetoresistance in the high-field limit reduces to $\rho(\infty)/\rho(0)=(1-\frac{1}{4}r^2)(1-r^2)^{-1/2}$. Hence, in this particular case, the high-field magnetoresistance diverges when the scattering is maximally anisotropic ($r=\pm 1$), which corresponds to the appearance of "zeroes" for the scattering rate (5) that are either along the major or the minor axes of the pocket Fermi surfaces. On the other hand, in the case of infinitely eccentric hole pockets, $m_x/m_y\to\infty$, which is the relevant limit to consider in the context of doped 2D antiferromagnets,[8] expression (9) reduces to $\rho(\infty)/\rho(0)=(r^{-1}-\frac{1}{2})[(1+r)^{1/2}(1-r)^{-1/2}-1]$. This expression diverges only when the anisotropy parameter is given by $r=1$, which is a situation that corresponds to the appearance of "zeroes" for the scattering rate (5) along the minor axis alone of the pocket Fermi surfaces. Given that we have implicitly assumed that the mechanism limiting in-plane transport is quasielastic, and that the density of states in the direction of coherent hole motion (π,π) corresponding to the minor axis of the hypothesized eccentric Fermi surface is relatively small, then such a value for the anisotropy parameter may well describe the scattering of charge carriers in a doped 2D antiferromagnet.

In the present context of the magnetotransport in underdoped lanthanum cuprates, this argument suggests that the saturation value for the high-symmetry transverse magnetoresistance could be high, which is consistent with our findings. We will now show, however, that the high-field magnetoresistance (9) that we obtain results in a weak effect for reasonable estimates of the input parameters. Suppose, in the case of the present hole concentration of $x=0.075$, that we take a mass anisotropy of $m_x/m_y=5.25$ for the hole bands, which is close to that obtained by Trugman in his study of doped 2D antiferromagnets at similar concentrations.[8] Suppose, further, that the scattering mechanism giving rise to (5) is quasieleastic. Since quasielastic transport rates $\tau_{\rm tr}^{-1}(\mathbf{k}')$ are proportional to the density of states at the point $\mathbf{k}'$ on the Fermi surface, the latter assumption implies that

$$\frac{m_y}{m_x}\cong\frac{\tau_0^{-1}-\tau_1^{-1}}{\tau_0^{-1}+\tau_1^{-1}} . \tag{10}$$

Inverting the above relation, we obtain

$$r=\frac{\tau_0}{\tau_1}\cong\left[1-\frac{m_y}{m_x}\right]\Big/\left[1+\frac{m_y}{m_x}\right] \tag{11}$$

for the scattering anisotropy parameter, which in the present case yields $r\cong 0.7$. Substituting these estimates into the previous expression (9), we obtain a high-field magnetoresistance saturation value of $\rho(\infty)/\rho(0)\cong 1.3$. That is, reasonable estimates for the input parameters based on the dynamics of doped 2D antiferromagnets predict a positive high-symmetry magnetoresistance effect in the presently studied compound that has a saturation value approximately 30% larger than the zero-field resistance. Notice that despite the presumed large anisotropy, the effect remains modest,[5] and also that the calculated value for the saturated transverse magnetoresistance is nearly two orders of magnitude larger than that measured at 40 K and 10 T [see Fig. 3(a)]. Last, we remark that because the assumed Fermi surface does not have axial symmetry about fields applied in the basal plane, we expect the longitudinal magnetoresistance to be positive as well, while being less than the transverse magnetoresistance.[5]

IV. DISCUSSION

The principal result presented in this paper was the observation of a positive in-plane magnetoresistance in the normal phase ($T>23$ K) of $La_{1.925}Sr_{0.075}CuO_{4+\delta}$. In particular, the high-symmetry transverse effect was found to be almost an order of magnitude larger than the longitudinal effect, with each scaling as $\Delta\rho(H)/\rho(0)\sim(H/T)^2$, and there was no evidence seen for saturation. The latter temperature dependence is consistent with the T-linear dependence observed at high-temperatures in the zero-field in-plane resistance (see Fig. 1). We note that a similar positive magnetoresistance behavior was previously observed in $Bi_2Sr_2CuO_6$ at comparable temperatures.[6] To interpret our results, while remaining consistent with Hall effect measurements,[1] we introduced a semiphenomenological picture based on the existence of eccentric hole-pocket Fermi surfaces located at the antiferromagnetic points (see Fig. 5). Such hole pockets are thought to exist in doped 2D antiferromagnets.[8] Given that the assumed anisotropy in the hole pocket engenders a corresponding anisotropy in the quasielastic transport rate, we found that a positive high-field magnetoresistance resulted for the case of the high-symmetry transverse geometry. Interestingly, we predict that no saturation effect occurs in the limiting case of infinite mass anisotropy corresponding to the existence of perfectly coherent hole motion along (π,π).

Many important issues connected with the presented study remain unresolved. The weak-field effect relevant to the current observations is left to be unraveled within the hole-pocket picture. In addition, as has been remarked in the literature,[6] the positive longitudinal magetoresistance that we observe is puzzling. This effect could be accounted for by taking the three-dimensional nature of the hypothesized hole-pocket Fermi surfaces into consideration, which has not been explored. We hope to address these issues in a future publication.

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*Permanent address: Natl. High Magnetic Field Lab., Pulsed Field Facility, Los Alamos Natl. Lab., Los Alamos, NM 87545.
†Permanent address: Dept. of Physics and Astronomy, California State University, Los Angeles, CA 90032.
‡Present address: Ames Lab., Iowa State University, Ames, Iowa 50011.

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