Anomalous Enhancement of the Electron Dephasing Rate from Magnetoresistance Data in $Bi_2Sr_2CuO_6$

T. W. Jing, N. P. Ong, and T. V. Ramakrishnan[(a)]
Joseph Henry Laboratories of Physics, Princeton University, Princeton, New Jersey 08544

J. M. Tarascon and K. Remschnig
Bell Communications Research, 331 Newman Springs Road, Redbank, New Jersey 07701

(Received 25 February 1991)

The low-temperature magnetoresistance (MR) in $Bi_2Sr_2CuO_6$ is highly anisotropic. By fitting the orbital MR with the weak-localization expression, we derive a carrier dephasing rate $1/\tau_\phi$ that varies as $T^{-1/3}$. This implies that the energy levels are greatly broadened at low temperatures. Both the energy scale derived from $1/\tau_\phi$ vs T and the behavior of the longitudinal MR suggest a strong coupling between the holes and the Cu spins. We discuss implications of the large dephasing rate, and contrast the MR with that of conventional disordered metals.

PACS numbers: 72.15.Rn, 72.15.Lh, 73.20.Fz, 74.70.Vy

In the high-temperature superconducting layered cuprates, a number of interesting issues are raised by the normal-state transport properties [1,2]. In the single-plane compound $Bi_2Sr_2CuO_6$ (Bi 2:2:0:1), the linear temperature dependence of the in-plane resistivity ρ_a extends from 6 to 600 K [3]. Infrared measurements [4] also show that the transport scattering rate $1/\tau_{tr}$ in $YBa_2Cu_3O_7$ and Bi 2:2:1:2 varies linearly with temperature, as $\hbar/\tau_{tr}=\eta k_B T$, where η lies between 2 and 3. The ubiquity of the linear resistivity and the wide temperature range over which it is observed imply a metallic state with unusual, and as-yet poorly understood, low-energy charge-carrying excitations. The nature of these excitations, and the role played by spin degrees of freedom in charge transport, can be probed further through the effects of magnetic field and disorder at low temperatures. Such quantum transport effects have provided detailed insights into carrier interactions, scattering processes, and inelastic length scales in disordered metals [5–8].

A quantitative comparison of the normal-state magnetoresistance (MR) with existing theory has not been attempted, although a few measurements exist [9,10]. We report here the observation of novel, highly anisotropic MR in Bi 2:2:0:1 in the temperature range 0.5–20 K. Below ~20 K, the (transverse) MR is observed to be negative when the field **H** is aligned normal to the CuO_2 planes (**H**‖**c**), but predominantly positive when the field is parallel to the applied current (**H**‖**I**, longitudinal MR). By fitting the transverse MR with the weak-localization expression, we uncover a carrier dephasing rate that has a highly unusual temperature dependence. The longitudinal MR, which directly probes the Zeeman contribution to the MR, shows a much richer behavior than expected from standard interaction theory.

To investigate the low-temperature transport behavior, we selected two crystals of Bi 2:2:0:1 that remain normal to ~0.2 K, but display a resistivity linear in T between ~20 and 300 K. In zero field, ρ_a goes through a minimum and then increases slowly as $-\ln T$, as the temperature decreases below ~18 K, consistent with the onset of localization (Fig. 1, inset). The linear ρ_a vs T behavior above 18 K extrapolates at $T=0$ to a resistivity value of 140 $\mu\Omega$ cm. The Hall coefficient R_H (1.47×10^{-9} m^3/C) is temperature independent, and corresponds to a hole density of 4.25×10^{21} cm^{-3} (or 0.75 per Cu ion) [11]. From R_H and ρ_a at 10 K, we compute a 2D Fermi wave vector k_F equal to 5.74×10^7 cm^{-1}, and a metallic parameter $k_F l_{tr}$ equal to 23 at 10 K (l_{tr} is the transport mean free path). This corresponds to an l_{tr} of ~40 Å at 10 K.

Figure 1 displays the transverse magnetoresistance ΔR_T vs H, observed when the field is perpendicular to the

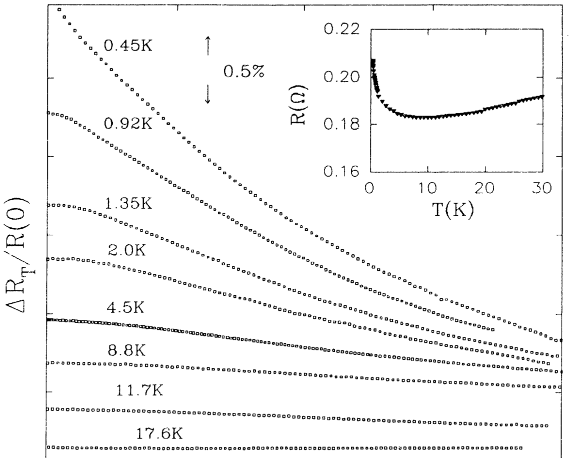

FIG. 1. Variation of the in-plane resistivity with field applied normal to the CuO_2 plane in Bi 2:2:0:1 (sample 1). The magnetoresistance is negative at all temperatures below 20 K. Inset: The in-plane resistance vs temperature below 30 K. Between 0.4 and 18 K, the conductivity correction fits well with $\Delta\sigma/\sigma = A\ln T$, where $A=3.75\times10^{-2}$.

planes (**H**∥**c**). At each temperature, the MR curve shows a crossover from negative curvature at low fields to positive curvature at high fields. (Sample 2 shows very similar results.) These curves recall the MR behavior in conventional metals in the weak-localization regime, except that the field scales here are 10 to 50 times larger at comparable temperatures (indicating unusually short dephasing times) [5-8]. To contrast this behavior, we display in Fig. 2 the longitudinal MR (ΔR_L vs H) observed when **H** is parallel to the current. Above 3 K, the quadratic increase of ΔR_L is apparent up to our highest field. Since ΔR_L involves only spin degrees of freedom, it is natural to reference the data to the Zeeman field scale $B_z = k_B T / g\mu_B$ (k_B is Boltzmann's constant, and μ_B the Bohr magneton). In fields well above B_z, the spin degrees are strongly suppressed, and this should be reflected in a saturation of the longitudinal MR [6]. However, at all temperatures investigated, the quadratic increase in ΔR_L extends well above B_z ($B_z \approx 0.71$ T at 1 K, if $g = 2$). The longitudinal MR is also complicated by the appearance of a new anomaly at temperatures below ~2 K. In the upper set of curves in Fig. 2, the longitudinal MR is *negative* in low fields. Competition between the negative and positive terms leads to a minimum in ΔR_L near 2.3 T.

In weak-localization theory, corrections to the conductivity arise when carriers diffuse around a self-intersecting path [5,6]. Constructive interference between a path and its time-reversed partner results in an enhancement of the amplitude for the carrier to return to the intersection. When a field is applied normal to the plane, the interference is suppressed, leading to a negative contribution to the MR. For two-dimensional (2D) systems, the correction $\Delta\sigma$ to the conductivity (without interaction) is [6-8]

$$\Delta\sigma = -\frac{\alpha e^2}{2\pi^2\hbar}\left[\psi\left(\tfrac{1}{2} + 1/\Omega\tau\right) - \psi\left(\tfrac{1}{2} + 1/\Omega\tau_\phi\right) - \ln(\tau_\phi/\tau)\right], \qquad (1)$$

where ψ is the digamma function, τ_ϕ the dephasing time, τ the elastic-scattering time, $\Omega = 4eHD/\hbar$, D the diffusion constant, and α a constant of order 1.

To compare our results with weak-localization theory, we assume that the longitudinal MR involves the spin degrees of freedom alone, and that these contributions are isotropic (negligible spin-orbit coupling). The orbital contributions to the transverse MR may be obtained by subtracting the longitudinal MR from the transverse, i.e., $\Delta R_{\text{orb}} = \Delta R_T - \Delta R_L$. We then fit ΔR_{orb} by Eq. (1). In general, very good fits are achieved at temperatures between 2 and 20 K (Fig. 3). Below 2 K, the appearance of the negative anomaly in ΔR_L (and hence in ΔR_{orb}) complicates the fits. However, restricting the fit to data above 2.5 T at these low temperatures, ΔR_{orb} can be fitted to the same precision as the curves in Fig. 3. The weak-localization correction accounts for $\sim\frac{1}{3}$ of the $\ln T$ correction in the inset of Fig. 1 [12].

In both samples, values of $l_0 = v_F\tau$ derived from the fits lie between 55 and 70 Å. These are slightly larger than the value of l_{tr} (40 Å) deduced above. The "dephasing" length $L_\phi = (D\tau_\phi)^{1/2}$ extracted from the fits increases from ~70 Å, near 20 K, to 140 Å at 0.4 K. As displayed in Fig. 4, the data from both samples are consistent with the relationship $L_\phi^2 = 131 T^{-1/3}\,\text{nm}^2$; i.e., the dephasing rate $1/\tau_\phi$ varies as the *cube root* of the temperature. Es-

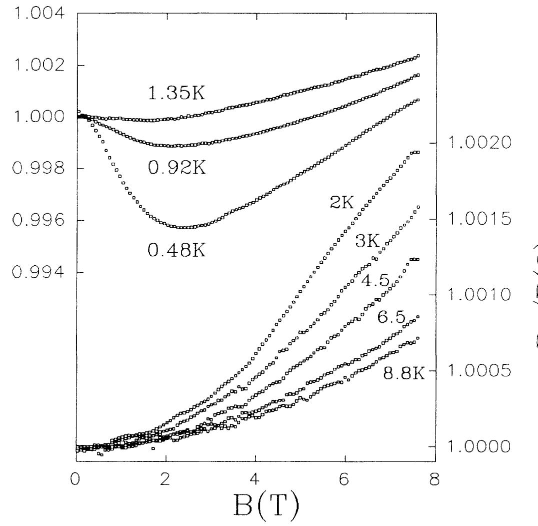

FIG. 2. The longitudinal magnetoresistance (**H**∥**I**) in a Bi 2:2:0:1 single crystal at temperatures below 10 K (sample 1). R_L is shown normalized to its value in zero field. At 2 K and above (lower set of curves), the MR is positive and monotonic; below 2 K (upper set), a negative contribution dominates at low fields. The vertical resolution of the upper set of curves is 5 times smaller than the lower set.

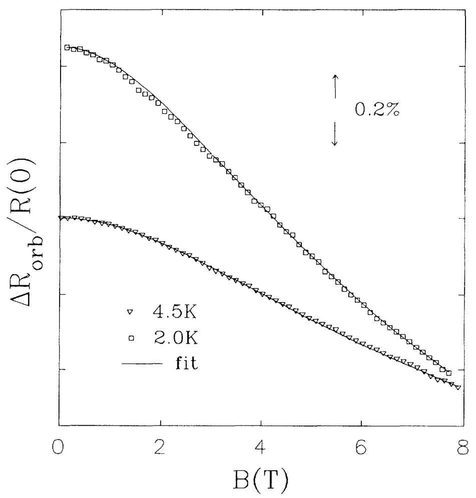

FIG. 3. Fits of the orbital component of the transverse MR, ΔR_{orb}, with the weak-localization expression [Eq. (1)] in sample 1. The fit parameters at 2.0 K (4.5 K) are $\alpha = 2.15$ (2.36), $l_0 = 65$ Å (58 Å), and $L_\phi = 102$ Å (87 Å).

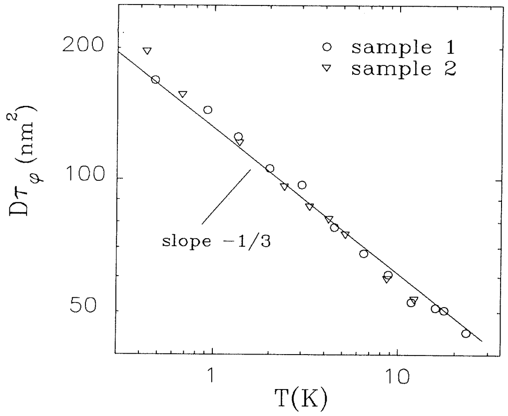

FIG. 4. Variation of the square of the dephasing length $L_\phi^2 = D\tau_\phi$ with temperature for samples 1 (circles) and 2 (triangles). The solid line (slope $-\frac{1}{3}$) implies a carrier dephasing rate that varies at $T^{1/3}$.

timating $D \approx 1.33\times 10^{-3}(m_0/m^*)$ m^2/s from the measured $k_F l_{\mathrm{tr}}$, we find that the dephasing rate is (setting the effective-mass ratio m^*/m_0 to 1)

$$1/\tau_\phi \approx 1.02\times 10^{13} T^{1/3}\,\mathrm{s}^{-1}. \tag{2}$$

The $T^{1/3}$ dependence is in striking contrast to the nearly linear-temperature variation widely observed in the disordered 2D electron gas found in thin films and semiconductor devices [6]. These numbers suggest that, in the low-temperature limit, the energy levels are greatly broadened compared with k_BT ($\hbar/\tau_\phi \approx 78 k_BT$ at 1 K). The enhanced rate indicates that carrier scattering by Coulomb interaction is much stronger than in conventional metals: At 0.5 K, the holes diffuse an average distance of ~140 Å before dephasing.

The values of L_ϕ shown in Fig. 4 are for temperatures at which the derivative $d\rho_a/dT$ is negative. When the temperature rises above ~20 K, we cross, fairly abruptly, into the important "linear-resistivity" regime. In this regime, the dephasing rate is equal to the inverse transport lifetime, i.e., $\hbar/\tau_\phi \approx \eta k_BT$. [The magnitude of L_ϕ deduced from Eq. (1) is close to l_0 when the crossover occurs.] We observe that, with increasing temperature above 20 K, the MR becomes more *isotropic* (independent of field orientation) and positive. The high-temperature MR, which suggests that important changes occur in the carrier relaxation processes when we enter the linear-temperature regime, will be reported elsewhere.

Next, we turn to the geometry in which **H** is aligned parallel to **I**. In this orientation, the magnetoresistance arises from coupling of the field to the spin degrees of freedom. In standard "interaction" theory [6,13], corrections to the propagators in the particle-hole channel occur for both singlet and triplet states. When the Zeeman energy exceeds k_BT, the singlet contributions are suppressed, leading to a positive longitudinal MR [13]. If we apply this picture to the data in Fig. 2, we find poor agreement with our experiment. A major difficulty is that the field scales in ΔR_L are neither of the order of the Zeeman field $B_z = k_BT/g\mu_B$ nor linear in temperature. To see this, we compare B_z with an empirical field scale B_s extracted from the data. Above 2 K, the longitudinal MR is quadratic in H at low fields, so that B_s may be defined by $\Delta R_L/R(0) \approx (B/B_s)^2$. Our data for B_s roughly follow the power law ($\gamma = 0.4$)

$$B_s(\mathrm{T}) = 105 T^\gamma \quad (2 < T < 10\,\mathrm{K}). \tag{3}$$

The field scale B_s is not obviously related to B_z. [As indicated in Eq. (3), B_s may be reliably determined only between 2 and 10 K.] The negative anomaly itself presents an additional difficulty for the standard interaction theory, which predicts only positive longitudinal MR.

Thus, the longitudinal MR behavior at low temperatures is much richer than expected from simple spin-polarization effects. There appear to exist at least two field scales (corresponding to the positive and negative contributions), neither of which matches precisely the Zeeman field scale B_z. The field scale in Eq. (3) is clearly much larger than B_z. An interesting possibility is that, when the dephasing rate greatly exceeds k_BT, the spin-splitting field should be determined by equating $g\mu_B B$ to $\hbar/\tau_\phi$, rather than to k_BT [14]. With this new cutoff, we calculate [15] a field scale B_s that has a $T^{1/3}$ dependence [i.e., closer to $\gamma = 0.4$ in Eq. (3)], but the predicted magnitude [15] of B_s is too large by a factor of 24, so this simple modification is inadequate. The observed field scale determining the quadratic increase in R_L seems to be intermediate between the conventional Zeeman field B_z and the rescaled field B_z^*. Another obvious source of positive MR, namely, superconducting fluctuations, may also be excluded. We have performed detailed studies on three other crystals that display superconducting transitions between 0.3 and 0.1 K. Detailed comparison enables us to exclude the existence of superconducting fluctuations in the two samples studied here [16].

The analysis reported here shows that the orbital MR is surprisingly well described by the weak-localization correction [Eq. (1)]. However, the detailed fits do not necessarily mean that the carriers in the CuO$_2$ planes are conventional fermions, but only that they are quantum particles with associated generic interference effects in a disordered medium. The fits disclose an unusually short dephasing length L_ϕ and a large dephasing rate that varies as $T^{1/3}$, instead of the familiar linear-T dependence. This strong enhancement may be intimately related to the widespread tendency of ρ_a to switch abruptly to localization behavior at low temperatures in the hole-type cuprates. The large dephasing rate also implies that the level widths are much larger than k_BT (by a factor of 78 at 1 K). This greatly violates a basic assumption of the Fermi-liquid picture, and invites careful reexamination of how the charge carriers should be described in the limit

$T \rightarrow 0$. We expect that further low-temperature MR studies will help elucidate the question whether the Fermi-liquid description is valid. The fractional power law of τ_ϕ implies the existence of an energy scale $E_\phi \sim 684$ K that is about half the copper spin-exchange energy J [17]. This suggests that the carrier dephasing rate is dominated by coupling to low-energy excitations of the Cu spins, and reinforces the picture in which motion of the charge carriers involves a rearrangement of the spin background in the cuprates. Coupling of the holes to the spin degrees is also important in the regime above 20 K where ρ_a is linear in T. With rising temperature, the negative transverse MR in Fig. 1 changes sign, and becomes increasingly similar to the longitudinal MR. In both orientations, ρ_a increases approximately *linearly* with field, for H between 1 and 8 T. The isotropic MR at high temperatures implies that **H** affects the conductance through the spin degrees, but the positive sign and the linear field dependence are difficult to account for. Thus, in addition to the anomalous dephasing rate, the MR experiments disclose a rich pattern of behavior involving the spins that does not fit the usual picture of disordered metals. Nonetheless, magnetoresistance is a potentially incisive probe of the hole dynamics. An understanding of relaxation processes in the localization regime, how they are affected by fields and how they change when the sample crosses into the linear-T regime, may provide important insights to the occurrence of superconductivity in the cuprates.

We are indebted to P. B. Wiegmann for motivating these studies. Valuable discussions with E. Abrahams, P. W. Anderson, A. G. Aronov, H. Fukuyama, G. Kotliar, and P. A. Lee are also acknowledged. This work is supported by the Office of Naval Research (Contract No. N00014-90-J-1013) and by a grant from the Seaver Institute.

---

[a] On leave from the Indian Institute of Science, Bangalore, India.

[1] *High Temperature Superconductivity*, edited by K. S. Bedell, D. Coffey, D. E. Meltzer, D. Pines, and J. R. Schrieffer (Addison-Wesley, Reading, MA, 1990).

[2] See P. W. Anderson and Y. Ren, in *High Temperature Superconductivity* (Ref. [1]), p. 3.

[3] S. Martin, A. T. Fiory, R. M. Fleming, L. F. Schneemeyer, and J. V. Waszczak, Phys. Rev. B **41**, 846 (1990).

[4] K. Kamaras *et al.*, Phys. Rev. Lett. **64**, 84 (1990); L. Forro *et al.*, Phys. Rev. Lett. **65**, 1941 (1990).

[5] For a review, see Gerd Bergmann, Phys. Rep. **107**, 1 (1984).

[6] For a review, see P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1985).

[7] S. Hikami, A. I. Larkin, and Y. Nagaoka, Prog. Theor. Phys. **63**, 707 (1980).

[8] D. J. Bishop, R. C. Dynes, and D. C. Tsui, Phys. Rev. B **26**, 773 (1982).

[9] N. W. Preyer, M. A. Kastner, C. Y. Chen, R. J. Birgeneau, and Y. Hidaka (to be published) have observed *isotropic* and negative MR in $La_{2-x}Sr_xCuO_{4+y}$ single crystals that are lightly doped ($0.02 < x < 0.1$).

[10] A. T. Fiory, S. Martin, R. M. Fleming, L. F. Schneemeyer, and J. V. Waszczak, Phys. Rev. B **41**, 2627 (1990). The Bi 2:2:0:1 crystals studied in this reference have large localization corrections to ρ_a, and $k_F l_{tr}$ values (3–5) much smaller than ours. The MR is strongly contaminated by superconducting fluctuation contributions.

[11] The interplane spacing and sheet resistance are 12.3 Å and 1.14 kΩ/□, respectively. See also L. Forro, D. Mandrus, C. Kendziora, L. Mihaly, and R. Reeder, Phys. Rev. B **42**, 8704 (1990).

[12] The coefficient A of the $\ln T$ term in $\Delta\sigma/\sigma$ (Fig. 1, inset) is ~ 3 times larger than $\alpha p/\pi k_F l_{tr} \approx 1.1 \times 10^{-2}$, if $p = \frac{1}{3}$ and $\alpha = 2.4$. Thus, interaction corrections, $\Delta\sigma/\sigma = (1-F)/(\pi k_F l_{tr}) \ln T$, account for $\sim \frac{2}{3}$ of the logarithmic change (F is a screening parameter).

[13] P. A. Lee and T. V. Ramakrishnan, Phys. Rev. B **26**, 4009 (1982).

[14] C. Castellani, C. DiCastro, G. Kotliar, and P. A. Lee, Phys. Rev. Lett. **56**, 1179 (1986).

[15] In Lee and Ramakrishnan [13], the fractional change in R (at low fields) is given by $\Delta R/R \approx (0.084F/2\pi k_F l_{tr}) \times (B/B_z^*)^2$. Using $B_z^* = \hbar/\tau_\phi g \mu_B \approx 57 T^{1/3}$ and assuming both F and $m^*/m_0 = 1$, we calculate B_s(T) to be $2400 T^{1/3}$.

[16] In superconducting crystals, the MR contributions arising from suppression of the superconducting fluctuations are unmistakable. They are positive for *both* **H**‖**c** and **H**‖**I** (in contrast with Figs. 1 and 2), and vary sharply with H near zero field. For a sample with $T_c \approx 0.1$ K, these contributions are ~ 10 times larger than the weak-localization corrections at 0.5 K. If present, they would render the latter unobservable.

[17] By writing $\hbar/\tau_\phi k_B T = (E_\phi/T)^{2/3}$, we find that $E_\phi \approx 684$ K, if $m^* \approx m_0$. We thank P. A. Lee for this observation.