Normal-state magnetoresistance of Sr_2RuO_4

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We report measurements of the in-plane and out-of-plane magnetoresistance (MR) of single crystals of the layered perovskite superconductor Sr_2RuO_4 ($T_c \approx 1$ K). The transverse c-axis MR $\Delta\rho_c/\rho_c(B)$ ($I \| c, B \| ab$) varies linearly with field at low temperatures consistent with the behavior expected for a quasi-two-dimensional Fermi surface in the intermediate-field regime. $\Delta\rho_c/\rho_c(T)$ shows a striking temperature dependence which arises from the competing effects of two separate MR contributions. At low temperatures, $\Delta\rho_c/\rho_c$ is large and positive due to the orbital magnetoresistance of the carriers. At high temperatures, however, $\Delta\rho_c/\rho_c$ is dominated by a negative MR term that is associated with the nonmetallic out-of-plane resistivity $\rho_c(T)$. We argue that the two contributions to $\Delta\rho_c/\rho_c(B,T)$ originate from separate conduction channels along the c axis and that the competition between the metallic and nonmetallic channels is responsible for the unusual temperature dependence of $\rho_c(T)$. Finally, we discuss the relevance of these findings to our current understanding of the unusual magnetoresistance of the high-T_c cuprates. [S0163-1829(98)09409-0]

I. INTRODUCTION

The anomalous behavior of the out-of-plane conductivity is one of the key challenges to our understanding of the high-T_c cuprate superconductors.[1] Recent measurements on optimally doped $Bi_2Sr_2CuO_6$ have revealed that even below 1 K, $\rho_c(T)$ is divergent while the in-plane resistivity $\rho_{ab}(T)$ is metallic,[2] thus rendering invalid any simple band-structure model in which the conductivities are scaled by an anisotropic transfer integral. Even in overdoped cuprates, where ρ_c is ''metallic'' (i.e., increasing with T), the anisotropy ratio ρ_c/ρ_{ab} is temperature-dependent and l_c, the mean-free path along the c axis, is shorter than the interplanar spacing d over a wide temperature range suggesting the possibility of charge confinement and incoherent charge transport between the planes.

Several magnetoresistance studies of the layered cuprates with current applied along the c axis have recently been published, shedding new light on the behavior of the interlayer charge dynamics. In overdoped cuprates,[3,4] $\Delta\rho_c/\rho_c$ ($I \| c, B \| ab$) is large and positive and shows several features that are consistent with three-dimensional band formation, despite the fact that $l_c < d$. In underdoped compounds,[4,5] the c-axis MR is negative and independent of field direction and appears to be correlated with the nonmetallic behavior of $\rho_c(T)$.

The layered perovskite Sr_2RuO_4 is isostructural with the cuprate parent compound La_2CuO_4 and recent measurements have revealed that, in addition to becoming superconducting around 1 K,[6] its normal-state properties are consistent with those of a highly-correlated Fermi liquid.[7–9] Since Sr_2RuO_4 also has a similar anisotropy ratio to the cuprates ($\rho_c/\rho_{ab} \approx 1000$), it seems an ideal reference material. Furthermore, a great deal is already known about the Fermi surface in Sr_2RuO_4 from quantum oscillation experiments[9] and this allows us to make a direct comparison of the behavior of $\rho_c(T)$ with the predictions of Bloch-Boltzmann transport theory. Below 20 K, Sr_2RuO_4 behaves as a coherent three-dimensional but highly anisotropic metal with both ρ_c and ρ_{ab} varying as T^2 and $l_c > d$ ($d = 6.3$ Å), at least for the two dominant electron pockets.[9] In contrast to the cuprates, however, $\rho_c(T)$ goes through a maximum around 130 K then decreases monotonically.

Here we report a study of the magnetoresistance of Sr_2RuO_4 single crystals between 3 and 350 K in fields up to 15 T with current flow $I \| ab$ and $I \| c$ and magnetic field $B \| I$ and $B \perp I$. We find that the in-plane transverse magnetoresistance $\Delta\rho_{ab}/\rho_{ab}$ is positive and shows a simple temperature dependence, in contrast to the in-plane Hall effect that is complicated by multiband effects in Sr_2RuO_4.[10,11] At low temperatures, the c-axis transverse MR (labeled hereafter as TMR) is positive and extremely large ($\Delta\rho_c/\rho_c \approx 1.7$ in 15 T) and varies *linearly* with field in the intermediate-field regime, consistent with the behavior expected from band theory for a highly anisotropic, quasi-two-dimensional Fermi surface (FS) in this experimental geometry.[3,12] As T is raised, $\Delta\rho_c/\rho_c$ falls sharply and becomes negative above 75 K, even though ρ_c is still increasing with temperature. The TMR remains negative up to 300 K and becomes essentially equivalent to the longitudinal MR ($I \| B \| c$, labeled hereafter as LMR) above around 200 K.

We propose that the total TMR may be composed of two separate contributions that are observable over a wide temperature range. The positive term is attributed to the orbital

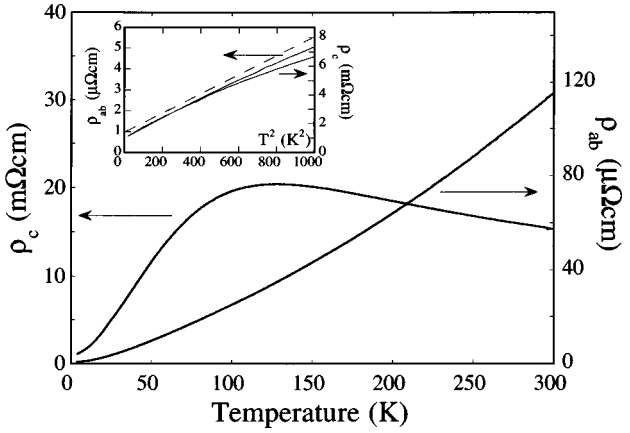

FIG. 1. Zero-field $\rho_{ab}(T)$ and $\rho_c(T)$ of Sr_2RuO_4. The inset shows $\rho_c(T)$ and $\rho_{ab}(T)$ below 32 K plotted against T^2. The dashed line is a guide to the eye.

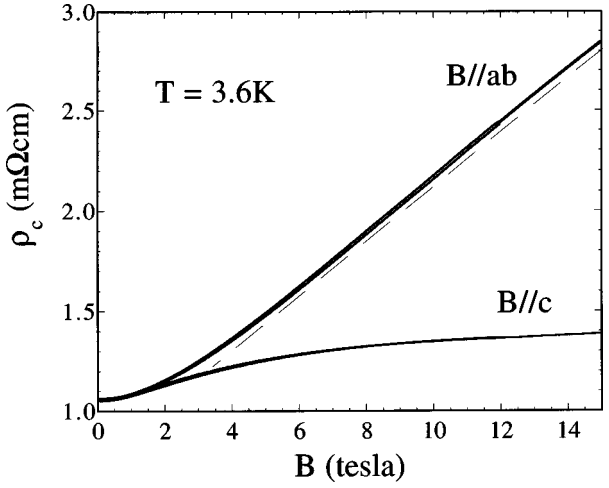

FIG. 2. c-axis MR field sweeps for Sr_2RuO_4 at $T=3.6$ K with $B\|ab$ and $B\|c$. The dashed line is drawn to highlight the region over which the transverse c-axis MR $\Delta\rho_c(B)$ is linear in field.

magnetoresistance of the carriers that persists well above 130 K, even though $l_c<d$ and $\rho_c(T)$ is nonmetallic. Being independent of field direction, the negative MR is thought to arise from magnetic-field effects on the spin degrees of freedom in the system and is associated with the nonmetallic contribution to $\rho_c(T)$. This is supported by the observation that there is no negative term in the in-plane MR. We propose that the combined c-axis MR and resistivity data of Sr_2RuO_4 can be qualitatively described in terms of two parallel conduction channels along the c axis, which leads naturally to the observed maximum in $\rho_c(T)$.

II. EXPERIMENTAL

The crystals used in this study were grown by a floating-zone method described elsewhere.[13] For the in-plane MR measurements, we used a single crystal (approximate dimensions 2 mm×0.5 mm×30 μm) that has already been studied in a series of quantum oscillation experiments[9] and a detailed in-plane Hall effect measurement.[11] Six contacts were mounted onto the crystal in the Hall geometry using Dupont 6838 silver paint. All six contacts were mounted in such a way that the c axis was shorted out electrically to ensure homogenous current flow within the plane. For the out-of-plane measurements, a single crystal from the same batch with approximate dimensions 0.5 mm×0.4 mm×50 μm was mounted in a quasi-Montgomery configuration. Large current and voltage pads were mounted on the top and bottom of the sample. Although the c axis was along the shortest dimension, $\rho_c(T,B)$ is reliable because of the large anisotropy (the equivalent isotropic crystal, obtained by multiplying the c-axis dimension by the square root of the resistivity anisotropy, has dimensions 0.5 mm×0.4 mm×1.8 mm at 30 K). A second thinner crystal was also mounted for studying $\rho_c(T)$. Although the aspect ratios of the two crystals were different, their $\rho_c(T)$ and $\Delta\rho_c/\rho_c(T)$ data were essentially equivalent, giving us confidence that, for the thicker crystal reported in this paper, the measured $\rho_c(T)$ was intrinsic to the c axis.

The zero-field resistivity data for each crystal are shown in Fig. 1. $\rho_c(T)$ reaches a maximum around 130 K then slowly decreases with increasing temperature up to 300 K, in agreement with other reported data.[6,13] Such behavior contrasts strikingly with that of the cuprates where often $\rho_c(T)$ is ''metallic'' at high temperatures, despite being well above the Mott-Ioffe-Regel limit (i.e., $l_c<d$), then as T is lowered, goes through a minimum and becomes semiconductinglike. The inset in Fig. 1 shows that below 20 K, both ρ_c and ρ_{ab} are varying as T^2 and the ratio $Y=\rho_c/\rho_{ab}$ is essentially T-independent with $Y\approx 1400$.

III. RESULTS

A. c-axis magnetoresistance–low-temperature limit

Figure 2 shows c-axis MR field sweeps at $T=3.6$ K with both $B\|ab$ and $B\|c$. The transverse MR (i.e., with $B\|ab$) is extremely large, the resistivity increasing by more than a factor of 2 in 15 T. As can be seen from the figure, the transverse MR $\Delta\rho_c/\rho_c$ varies linearly with field above around 3 T with no sign of saturation. This linear variation of $\Delta\rho_c/\rho_c$ is consistent with a treatment of standard Bloch-Boltzmann theory for quasi-two-dimensional metals in this field geometry[3,12] that predicts a $/B/^1$ decay of the magnetoconductance when one leaves the strictly weak-field ($-B^2$) limit and enters the intermediate-field regime. For such anisotropic compounds, this region extends over a wide field range,[12] namely, $1\leqslant\Omega_c\tau\leqslant\Omega_c\tau\langle\nu_\|\rangle/\langle\nu_\perp\rangle$ where $\Omega_c=(e/\hbar)\nu_\| Bd/\sqrt{2}$ and $\nu_\|$ and $\nu_\perp$ are the in-plane and out-of-plane Fermi velocities.

As T is raised, the magnetoresistivity is given simply by the weak-field expression $\rho=\rho^{(0)}+\rho^{(2)}$, where $\rho^{(2)}$ represents the term that is quadratic in field. For a single band metal, assuming an open FS with a circular cross section,[3] the B^2 term in the orbital c-axis MR $\Delta\rho^{(2)}/\rho^{(0)}$ is given by

$$\Delta\rho^{(2)}/\rho^{(0)}=\Omega_c^2\tau^2. \quad (1)$$

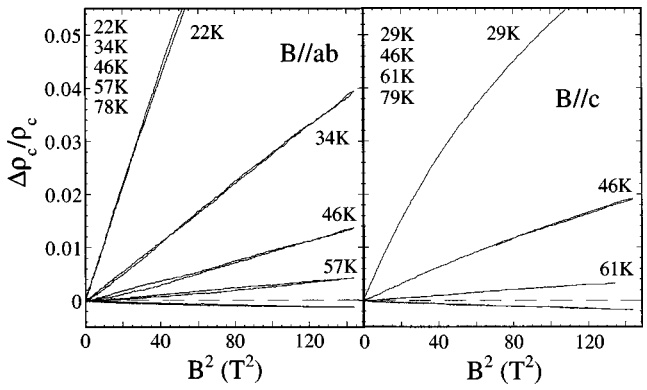

FIG. 3. c-axis MR field sweeps for Sr_2RuO_4 with $B\|ab$ (left panel) and $B\|c$ (right panel) at various temperatures between 20 and 80 K.

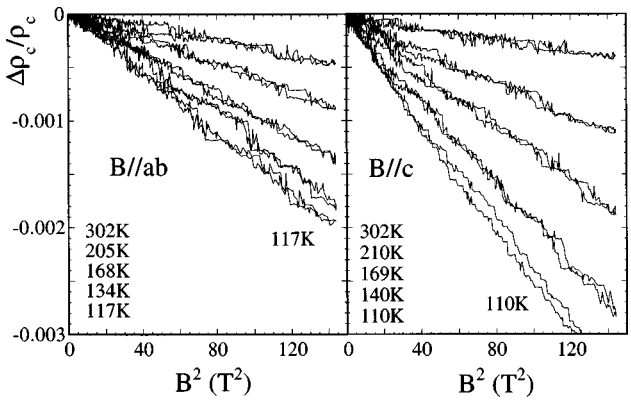

FIG. 4. c-axis MR field sweeps for Sr_2RuO_4 with $B\|ab$ (left panel) and $B\|c$ (right panel) at various temperatures between 100 and 300 K.

At the lowest temperatures, where the transport properties are dominated by large angle scattering from impurities, one can assume that the in-plane mean-free path $l_\parallel = v_\parallel \tau$ is limited only by the separation between the scattering impurities and is no longer sensitive to differences in the Fermi velocity either at different parts of the same FS sheet or on different sheets in the case of a multiband metal. This so-called ''isotropic-l'' approximation has been shown to work well in Sr_2RuO_4 at low T where measurements of the in-plane Hall coefficient below 1 K were found to be consistent with the value estimated from the known FS parameters.[11] Quantum oscillation experiments have revealed that the FS of Sr_2RuO_4 is composed of three cylindrical sheets with weak dispersion along the c axis.[9] Within the isotropic-l approximation, Eq. (1) is still valid for a multiband metal, since the fractional change in conductivity is the same for each band and the effects of the Hall conductivity can be ignored. In the same approximation, the in-plane resistivity in zero field is given by

$$\rho_{ab} = \frac{hd}{e^2 l_\parallel \Sigma_i k_F^i}, \tag{2}$$

where k_F^i are the Fermi wave vectors for each FS sheet $=0.3$, 0.62, and 0.75 Å^{-1}.[9] Using Eq. (1) and the experimental value of $\Delta\rho^{(2)}/\rho^{(0)}$ for the c-axis MR at 3.6 K, we find $l_\parallel \approx 1600$ Å. Then Eq. (2) gives a value for $\rho_{ab} = 0.6\ \mu\Omega$ cm, in good agreement with the measured value for our crystal at 3.6 K. This result illustrates further not only the applicability of the isotropic-l approximation, even in a multiband material, but also how an out-of-plane MR measurement on a quasi-two-dimensional metal can be used to obtain a reliable estimate for $l_\parallel$.

With the field applied parallel to the current ($B\|c$), we also observe a large positive MR at low temperatures that tends to saturate at high fields, as shown in Fig. 2. The positive longitudinal MR is surprising since the Lorentz force is absent in this orientation. A large positive MR has also been observed in $Tl_2Ba_2CuO_6$ (Ref. 14) and $La_{2-x}Sr_xCuO_4$ (Ref. 4), though its origin is not understood. It is possible that such a positive longitudinal MR may be spurious and due to some current redistribution in the crystal (e.g., due to poor crystallinity) that causes some of the carriers to trace orbits parallel to the ab plane. This is qualitatively consistent with the observation that the longitudinal MR is tending towards saturation at high fields as expected for contributions from closed orbits. However, one might expect in this case that the field dependence of the c-axis LMR would be identical to that of the in-plane TMR at the same temperature, which is not found experimentally. Another possibility is that this large c-axis LMR is in fact intrinsic, as suggested by direct c-axis resistivity measurements on long single-crystal bars of $La_{2-x}Sr_xCuO_4$,[4] and linked to the effect of the magnetic field on a warped cylindrical FS.

B. c-axis magnetoresistance–temperature dependence

Figure 3 shows the transverse (left panel) and longitudinal (right panel) c-axis MR field sweeps at various temperatures between 20 and 80 K. As T is raised, the positive MR in each case falls rapidly [much faster than τ^2, where τ^{-1} is proportional to $\rho_{ab}(T)$] and both become negative around $T = 75$ K. Representative MR field sweeps above 80 K, where the c-axis MR is now negative, are shown in Fig. 4. The MR for both field orientations decreases gradually with increasing temperature.

The T dependence of the B^2 parts in the transverse and longitudinal c-axis MR between 65 and 350 K are summarized in Fig. 5. [$\Delta\rho^{(2)}/\rho^{(0)}$ data at lower temperatures are not included in this plot to allow the high-temperature behavior to be shown in greater detail.] The TMR $\Delta\rho^{(2)}/\rho^{(0)}$ data, indicated by closed squares, go through a minimum around 120 K, then gradually becomes less negative with increasing T. Above 200 K, the TMR and the LMR (shown by open squares) become essentially equivalent, implying that the MR is ''isotropic,'' i.e., independent of the field direction. Below 200 K, the TMR becomes more positive than the LMR, presumably due to the extra positive orbital contribution to the TMR when $B\perp I$. We will return to this point later.

A negative isotropic MR has also been observed in some underdoped cuprates[4,5] and has been associated[5] with the effect of a magnetic field on the normal-state gap that is thought to exist in these materials. It has been suggested by several authors[15–18] that the normal-state gap acts as a barrier to interlayer charge transport in underdoped cuprates and

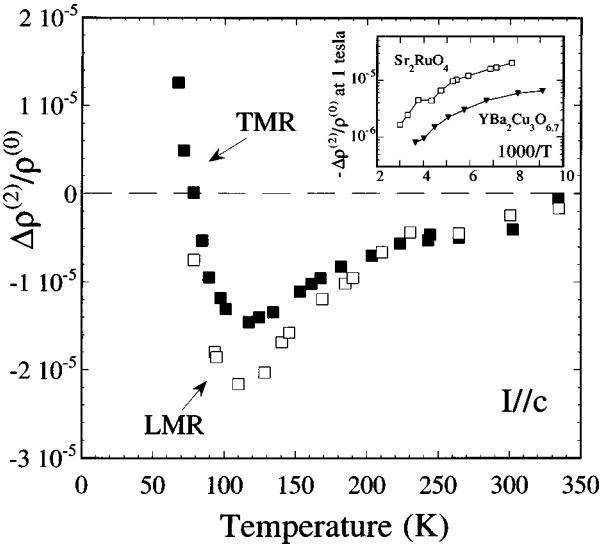

FIG. 5. Temperature dependence of the B^2 term in c-axis MR of Sr_2RuO_4 with $B\|ab$ (closed squares) and $B\|c$ (open squares) above 50 K. The inset shows the c-axis LMR data for Sr_2RuO_4 plotted as $\Delta\rho^{(2)}/\rho^{(0)}$ vs $1000/T$ together with similar data for $YBa_2Cu_3O_{6.7}$ taken from Ref. 5.

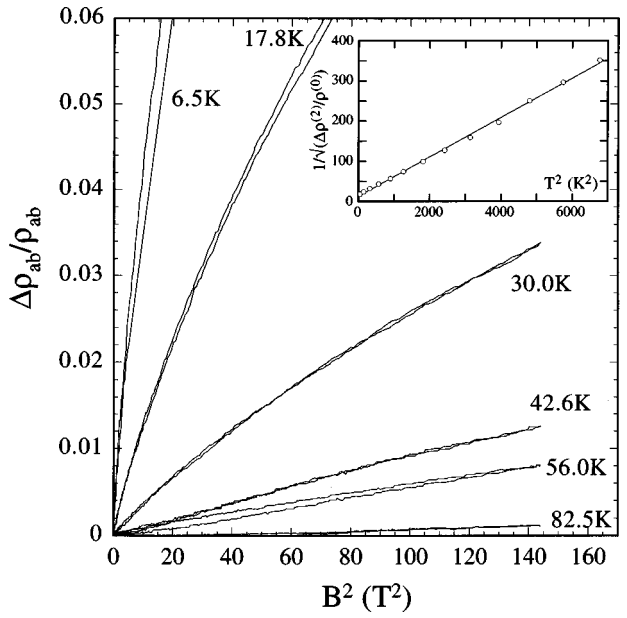

FIG. 6. In-plane MR field sweeps for Sr_2RuO_4 at various temperatures below 100 K with $B\|c$. The inset is a plot of $1/\sqrt{(\Delta\rho^{(2)}/\rho^{(0)})}$ vs T^2 for the in-plane transverse MR data (below 85 K).

plays a significant role in the behavior of $\rho_c(T)$ and the out-of-plane ac conductivity $\sigma_c(\omega)$. Within this picture, a magnetic field will suppress the gap and hence promote c-axis conduction. Even the existing data for the cuprates, however, are not universally consistent with this simple interpretation. The expected activated form for $\Delta\rho_c/\rho_c$ is observed in $Bi_2Sr_2CaCu_2O_8$,[5] but in underdoped $La_{2-x}Sr_xCuO_4$ (Ref. 4) and oxygen deficient $YBa_2Cu_3O_{6.7}$,[5] the temperature dependence of $\Delta\rho_c/\rho_c$ is different. As shown in the inset to Fig. 5, our data for Sr_2RuO_4 are similar in both magnitude and temperature dependence to those of $YBa_2Cu_3O_{6.7}$ and clearly do not follow the activated form that was observed in $Bi_2Sr_2CaCu_2O_8$. Since there is no evidence of a normal-state gap in Sr_2RuO_4, our data serve to emphasize that the observation of a negative isotropic c-axis MR in the cuprates should not necessarily be taken as evidence in favor of a normal-state gap affecting the c-axis conductivity.

C. *ab*-plane magnetoresistance

Figure 6 shows a series of in-plane TMR field sweeps from 10 to 85 K. (Above 85 K, the TMR became too small to be measured with sufficient accuracy.) At low T, the MR is again large and positive, though considerably smaller than the corresponding c-axis TMR. Below 50 K, $\Delta\rho_{ab}/\rho_{ab}$ varies quadratically at low fields then shows a tendency to saturate at higher fields as expected for contributions from closed orbits within the plane [this is seen most clearly with MR data taken below 1 K (Ref. 8)]. As T is raised, the field sweeps follow a B^2 dependence more closely and above 50 K, $\Delta\rho_{ab}(B)$ is quadratic over the entire field regime studied.

The inset to Fig. 6 shows the T dependence of the B^2 term of the in-plane TMR, plotted as $1/\sqrt{(\Delta\rho^{(2)}/\rho^{(0)})}$ vs T^2. Since $\Delta\rho^{(2)}/\rho^{(0)}$ is proportional to $\Omega_\|^2\tau^2$, the T dependence of $1/\sqrt{(\Delta\rho^{(2)}/\rho^{(0)})}$ should give the T dependence of the transport scattering rate. As can be seen from the inset in Fig. 6, $1/\sqrt{(\Delta\rho^{(2)}/\rho^{(0)})}$ can be well approximated by the expression $A+BT^2$. A similar T dependence has also been observed for the in-plane orbital MR of $YBa_2Cu_3O_7$ (Ref. 19) and for both the in- and out-of-plane MR of overdoped $Tl_2Ba_2CuO_{6+\delta}$.[3] It was noted that in both these cases, the square of the Hall angle $\tan\Theta_H$ has the same T dependence as $\Delta\rho^{(2)}/\rho^{(0)}$, since $\cot\Theta_H \approx A+BT^2$. Unfortunately this correspondence cannot be checked for Sr_2RuO_4, since the Hall effect of Sr_2RuO_4 shows a very complex behavior[10,11] due to the competing Hall contributions from the different FS sheets. Furthermore, the multiband nature of Sr_2RuO_4 prevents us from analyzing the T dependence of the orbital MR in too much detail.

The longitudinal in-plane MR was found to be positive and very small (e.g., $\Delta\rho^{(2)}/\rho^{(0)} \approx 4\times10^{-4}$ at 60 K and 12 T) with a very similar T dependence to the in-plane TMR. We believe that this small positive contribution is a fraction of the transverse component of the magnetoresistance due to a small misalignment of the crystal in the magnetic field. Significantly, there is no evidence for a negative MR term when $I\|ab$. This is an important point that we will return to in our discussion of the c-axis MR data.

IV. DISCUSSION

The data in Fig. 5 are consistent with a picture in which the c-axis TMR of Sr_2RuO_4 is composed of two separate contributions that individually extend over a wide temperature range. Specifically, the LMR is negative above 75 K in a region where $\rho_c(T)$ is still metalliclike and the difference between the TMR and the LMR, which is a measure of the orbital MR, remains appreciable up to 200 K, well above the ρ_c maximum. This latter observation is particularly intriguing, since above 30 K, l_c is known to be less than d for all

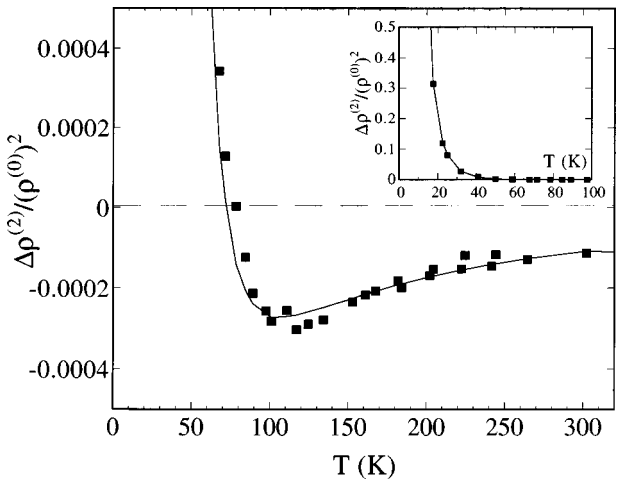

FIG. 7. The temperature dependence of the B^2 term in the c-axis TMR of Sr_2RuO_4 between 60 and 300 K (closed squares) plotted as $\Delta\rho^{(2)}/(\rho^{(0)})^2$. The solid line is a fit to $\Delta\rho^{(2)}/(\rho^{(0)})^2$ with the expression (valid for $\Delta\sigma \ll \sigma$) $\Delta\rho^{(2)}/(\rho^{(0)})^2 = \Delta\rho_B/\rho_B^2 + \Delta\rho_T/\rho_T^2$, where $\Delta\rho_B/\rho_B(T) = X\Delta\rho_{ab}/\rho_{ab}(T)$, $\rho_B(T) = Y\rho_{ab}(T)$, $\Delta\rho_T/\rho_T(T) = Z(H/T)^2$ and $\rho_T(T) = 1/[(1/\rho_c) - (1/\rho_B)]$. For this fit, $X = 2$, $Y = 1400$, and $Z = 0.39$. The inset is the same plot for $\Delta\rho^{(2)}/(\rho^{(0)})^2$ below 100 K.

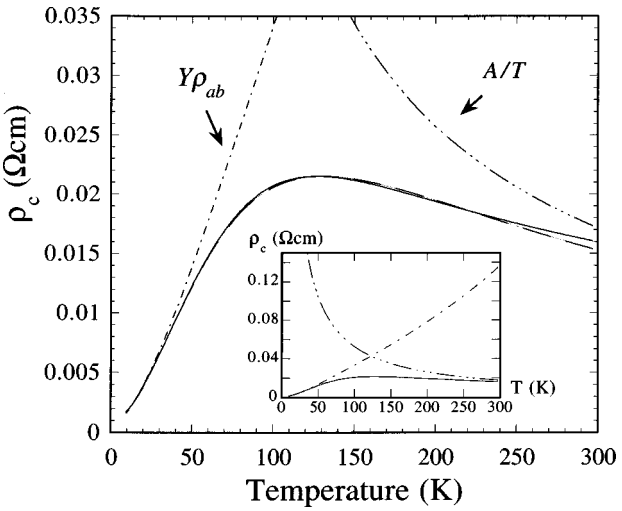

FIG. 8. Zero-field $\rho_c(T)$ of Sr_2RuO_4 (solid line) together with a fit to the expression $1/\rho_c(T) = 1/Y\rho_{ab}(T) + 1/(A/T)$ (dashed line). For this fit, $Y = 1400$, $A = 5.15\ \Omega$ cm. The two components of the resistivity fit are shown by dot-dash lines. The inset shows the same data on a different scale to highlight the behavior of the two terms over a wider temperature range.

three FS sheets,[9] implying diffusive rather than band propagation in the c direction at high T. It has been suggested[20,21] that when the c-axis hopping integral t_c becomes very small in anisotropic conductors, a large number of in-plane scattering events can take place before an electron hops or tunnels to an adjacent plane. In this incoherent case, t_c is renormalized to $t_c^2\tau_{ab}/\hbar \ll t_c$ (Refs. 20 and 21) and the c-axis MR and the out-of-plane conductivity are both dominated by the in-plane scattering rate τ_{ab}^{-1}. Indeed, in overdoped $Tl_2Ba_2CuO_{6+\partial}$ (Ref. 3) where no negative c-axis MR contribution is observed, $\Delta\rho_c/\rho_c$ is found to follow the T dependence of the in-plane TMR $\Delta\rho_{ab}/\rho_{ab}$ up to 300 K even though above 30 K, $l_c < d$. This behavior is somewhat puzzling but does suggest that the c-axis MR may be dominated at high T by scattering processes *within* the plane. However, for Sr_2RuO_4, $\rho_c(T)$ and $\rho_{ab}(T)$ show completely different behavior and hence some other mechanism must start to dominate the c-axis conductivity at higher T.

With this in mind, we have attempted here to fit the T dependence of $\rho_c(T)$ and $\Delta\rho_c/\rho_c(T)$ of Sr_2RuO_4 using a two-component model consisting of two parallel conduction channels (one metallic and one nonmetallic) along the c axis. In this case, the total c-axis resistivity is given by the expression $1/\rho_c(T) = 1/\rho_B(T) + 1/\rho_T(T)$ where $\rho_B(T)$ is the band-like term, which is known to be coherent at low T and that still represents some form of coherent or incoherent direct hopping at elevated T, and $\rho_T(T)$ is the nonmetallic term that originates from some completely incoherent tunneling process. For $\Delta\sigma \ll \sigma$, the total transverse c-axis MR is then given by the weighted sum of these two contributions, namely,

$$\frac{\Delta\rho_c}{\rho_c} = \frac{\sigma_B}{\sigma_c}\frac{\Delta\rho_B}{\rho_B} + \frac{\sigma_T}{\sigma_c}\frac{\Delta\rho_T}{\rho_T}, \tag{3}$$

or alternatively,

$$\left(\frac{\Delta\rho_c}{\rho_c}\right)\frac{1}{\rho_c} = \left(\frac{\Delta\rho_B}{\rho_B}\right)\frac{1}{\rho_B} + \left(\frac{\Delta\rho_T}{\rho_T}\right)\frac{1}{\rho_T}. \tag{4}$$

Before attempting to fit the TMR data to this two-component model we must first make some assumptions about the behavior of the individual terms in Eq. (4). Firstly, we assume that the band term $\rho_B(T)$ has the same T dependence as $\rho_{ab}(T)$ scaled only by the low T anisotropy ratio (i.e., $\rho_c/\rho_{ab} \approx 1400$). Similarly, the orbital MR contribution $\Delta\rho_B/\rho_B(T) = X\Delta\rho_{ab}/\rho_{ab}(T)$ where X is a scaling factor. This seems reasonable since in overdoped $Tl_2Ba_2CuO_{6+\partial}$ (Ref. 3) and $La_{2-x}Sr_xCuO_4$ (Ref. 4), $\Delta\rho_c/\rho_c(T)$ is proportional to $\Delta\rho_{ab}/\rho_{ab}(T)$ up to 300 K. We can fix X ($=2.0$) by comparing $\Delta\rho_c/\rho_c(T)$ and $\Delta\rho_{ab}/\rho_{ab}(T)$ at low temperatures (below 30 K) where this relationship is found to hold and the c-axis TMR is dominated by the orbital MR term. The tunneling resistivity $\rho_T(T)$ is given simply by $1/\rho_T(T) = 1/\rho_c(T) - 1/\rho_B(T)$. Finally, since the negative MR contribution is isotropic (at least above 200 K), we assume that it arises from a Zeeman splitting of the eigenstates involved in the incoherent hopping process. A negative isotropic MR can arise in nonmetallic systems when the hopping or tunneling rate is increased due to the occupation of the higher energy up-spin states by Zeeman splitting.[22,23] In a simple model where the carriers tunnel through an insulating barrier between the planes, $\Delta\rho_T/\rho_T(T)$ is expected to be equal to $Z(B/T)^2$ where $Z = 3/\pi^2(\mu_B/k_B)$.[23]

Figure 7 shows the resulting fit of the TMR data to Eq. (4), plotted as $\Delta\rho_c/\rho_c^2$ above 50 K and the inset shows the fit down to 15 K where $\Delta\rho_c/\rho_c^2(T)$ is very large. Although we have made several assumptions in fitting the TMR data, as listed above, there is only one parameter that has been allowed to vary, namely, Z, yet the fit is a reasonable one for all temperatures. A similar two-component fit to $\rho_c(T)$ in

zero field is shown in Fig. 8 in which $\rho_T(T)$ is approximated by a $1/T$ law.[24] Of course, it is quite likely that a full description of the T dependence of $\rho_c(T)$ and $\Delta\rho_c/\rho_c(T)$ will include other contributions (e.g., a T-dependent anisotropy ratio $Y(T)$ or thermal expansion effects on the incoherent hopping term), but we believe that Figs. 7 and 8 serve as illustrations that $\rho_c(T)$ and the c-axis TMR in Sr_2RuO_4 can be considered as arising from two separate conduction channels that coexist over the entire temperature range $3\,K<T<300$ K.

We have argued earlier that the isotropic negative c-axis MR observed in Sr_2RuO_4 and in the underdoped cuprates are of the same origin and both appear to be correlated with the nonmetallic $\rho_c(T)$. However, in the underdoped cuprates [and optimally doped $Bi_2Sr_2CuO_6$ (Ref. 2)], the out-of-plane transport cannot be considered as a simple two-component process since $\rho_c(T)$ has a *minimum* rather than a maximum. Instead, $\rho_c(T)$ probably contains multiplicative factors, e.g., $\rho_c(T)$ starts to rise at low T due, for example, to a reduction in the density of states caused by the opening of the normal-state gap[17] or $\rho_c(T)$ increases with T at higher T because of thermal expansion along the c axis.[25]

Several models describing $\rho_c(T)$ in the high-T_c cuprates[21,26–28] interpret the crossover from metalliclike to nonmetallic behavior as a transition from coherent to incoherent hopping with changing temperature rather than due to the coexistence of two competing conduction channels. Rojo and Levin proposed a two channel model,[29] in which the layered perovskites are considered as weakly coupled two-dimensional Fermi liquids. In this model, $\rho_B(T)$ again results from band motion characterized by t_c and proportional to τ_{ab}, while the second term $\rho_T(T)$ arises from impurity, phonon or spin-fluctuation assisted c-axis hopping. The combination of these two independent transport processes leads naturally to a maximum in $\rho_c(T)$ and a similar T dependence to that observed in Sr_2RuO_4. Recent measurements of the spin susceptibility,[7] specific heat[7] and electron spectroscopy[30] on single crystals of Sr_2RuO_4 suggest that there are strong on-site electron-electron correlations in Sr_2RuO_4 that could give rise to an appreciable spin-fluctuation spectrum in this system. However, assisted hopping via spin fluctuations might be expected to give rise to a *positive* rather than a negative contribution to the magnetoresistance. A more probable explanation is that the interlayer hopping term is due to phonon-assisted hopping, but for this to be the case, the c-axis phonon spectrum of Sr_2RuO_4 (Ref. 31) must be significantly different from that of overdoped $La_{2-x}Sr_xCuO_4$ and the other overdoped cuprates, where the incoherent hopping term appears to be completely absent. This possibility needs to be investigated further.

In the overdoped cuprates, whose c-axis TMR shows a similar behavior to the bandlike term $\Delta\rho_B/\rho_B$ in Sr_2RuO_4, there is no evidence of a negative MR nor of a crossover to a nonmetallic $\rho_c(T)$ at higher temperatures. This is probably the most striking difference between the c-axis resistivity of the cuprates and Sr_2CuO_4, since in both cases, $\rho_c(T)$ is of the same order and $l_c<d$ above around 30 K. In Sr_2RuO_4, we have argued that there are two parallel conduction channels along the c axis, yet in the overdoped cuprates, the nonmetallic channel is clearly absent. In order to discuss the origin of this contrasting behavior, we must consider which properties of Sr_2RuO_4 and the cuprates are significantly different, e.g., the different band structures of the two systems, the multiband nature of Sr_2RuO_4 or the effect of electron correlations. We already know that the c-axis dispersion of the small hole pocket in Sr_2RuO_4 (labeled α) is considerably smaller than that of the two larger electron pockets (β and γ) and significantly less than the band-structure prediction.[9] Simple band transport analysis from the individual FS parameters gives estimates of l_c for the α, β, and γ pockets of 3 Å, 36 Å, and <30 Å, respectively, implying that $l_c<d$ for the α pocket even at zero temperature and therefore the c-axis transport for the α pocket may be nonmetallic at all temperatures. However, it seems very unlikely that this small pocket could be solely responsible for the nonmetallic channel and dominate over the two large electron pockets above the maximum in $\rho_c(T)$.

Electron correlations are thought to be significantly stronger in the cuprates and may have some role to play in the different behavior for $\rho_c(T)$ that is observed. We note, however, that both a nonmetallic $\rho_c(T)$ and a negative isotropic c-axis MR are also observed in underdoped cuprates where correlation effects are expected to be even stronger. Finally, it has been suggested that the unusual behavior of $\rho_c(T)$ [and $\sigma_c(\omega)$] in the cuprates are signatures of charge confinement within the planes due to their non-Fermi-liquid ground state.[32] Many of the low-temperature properties of Sr_2RuO_4 are consistent with a model of a highly anisotropic Fermi liquid,[7] and therefore it might be argued that these differences between Sr_2RuO_4 and the overdoped cuprates, for example, are consistent with them having different metallic ground states. However, essentially all the features of $\rho_c(T)$ and the c-axis MR described here for Sr_2RuO_4 are observed in either the underdoped or the overdoped cuprates (but not in both) and so it becomes very difficult to say which properties are signatures of the particular ground state of each system.

V. CONCLUSIONS

In conclusion, we have made a detailed study of the in- and out-of-plane MR of Sr_2RuO_4 single crystals between 3 and 350 K. Our results show evidence for the existence of two contributions to the c-axis MR over a wide temperature range that can be thought to arise from two separate conduction channels. At low temperatures, $\Delta\rho_c/\rho_c$ is large and positive due to the orbital magnetoconductance of the carriers and appears to follow a similar temperature dependence to the in-plane orbital MR $\Delta\rho_{ab}/\rho_{ab}$ up to 200 K even though above 130 K, $l_c<d$ and $\rho_c(T)$ shows nonmetallic behavior. At high temperatures, $\Delta\rho_c/\rho_c$ is dominated by a negative isotropic MR term. Since there is no negative MR contribution for $\Delta\rho_{ab}/\rho_{ab}$ and $I\|ab$, we conclude that this negative isotropic MR is associated with the nonmetallic $\rho_c(T)$. Furthermore, the T dependence of the c-axis TMR in Sr_2RuO_4 mirrors the T dependence of $\rho_c(T)$ very well, implying that there is a close link between the two effects. These observations suggest a consistent explanation of the c-axis transport of Sr_2RuO_4 as follows: Below 30 K, the c-axis conductivity is dominated by the two large electron pockets and shows many features consistent with three-

dimensional band formation. Above 30 K, even though l_c of all three pockets become smaller than d, an orbital MR contribution and metalliclike conduction are still observed. As the temperature is raised, the conductivity becomes a combination of direct tunneling via t_c, which may become controlled by in-plane scattering events, and some form of incoherent c-axis hopping that eventually begins to dominate the transport above the maximum in $\rho_c(T)$ at 130 K.

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