Normal-state magnetotransport in superconducting $Tl_2Ba_2CuO_{6+\delta}$ to millikelvin temperatures

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We report a study of the normal-state Hall effect and magnetoresistance of single crystals of $Tl_2Ba_2CuO_{6+\delta}$. Using samples with $T_c < 15$ K, we can suppress the superconductivity down to low temperatures with magnetic fields of 16 T, and can thus study the normal state properties over three decades of temperature, extending into the $T \rightarrow 0$ limit where it is possible to make a reliable estimate of $k_F \sim 0.7$ Å^{-1} from the Hall effect in the elastic-scattering regime. The temperature dependence of the Hall coefficient, R_H, below 30 K rules out models in which $R_H(T)$ is taken as a measure of a real temperature-dependent change in the carrier concentration. The two scattering rates (probed by the resistivity and the cotangent of the Hall angle) which characterize normal-state transport in the cuprates also appear in this overdoped material for $T \geqslant 30$ K. However, as $T \rightarrow 0$, we observe only a *single* scattering rate, whose temperature dependence is dominated by low power terms, in contrast to the T^2 dependence predicted for a Fermi liquid. The relationship between these findings and anomalous behavior previously reported for the upper critical field is discussed.

I. INTRODUCTION

Soon after the discovery of the cuprate superconductors, it became clear that their normal-state properties have several unusual features. For example, in $YBa_2Cu_3O_{6.95}$ and several other materials, there is a strong linear term in the *ab*-plane resistivity, ρ, over a wide range of temperature (e.g., approximately 10–700 K in $Bi_2Sr_2CuO_6$[1]). Moreover, the Hall coefficient, R_H, has too strong a temperature dependence to be easily understood in materials whose transport is thought to be dominated by a single band.[2] Detailed study of materials covering a wider range of stoichiometry or "doping" shows that the temperature dependences of ρ and R_H vary appreciably across the superconducting phase diagram which is sketched in Fig. 1.[3–10] In particular, $R_H(T)$ changes in an apparently nonsystematic fashion, and this led to considerable difficulties in interpreting the data. An important step was made when Anderson suggested that the temperature dependence of R_H could be better understood in terms of two apparently decoupled scattering rates with different temperature dependences.[11] The resistivity (ρ) reflects the temperature dependence of $1/\tau_{tr}$, while the cotangent of the Hall angle ($\cot \Theta_H = \rho / R_H B$) is sensitive to $1/\tau_H$. R_H itself is sensitive to τ_H / τ_{tr}, and so in this picture is expected to have a more complex temperature dependence than ρ or $\cot \Theta_H$.

Anderson's suggestion was confined to optimally doped materials in which $1/\tau_{tr}$ varies linearly with temperature, and was quickly confirmed experimentally in $YBa_2Cu_3O_{7-\delta}$ doped with various levels of Zn impurities by Chien, Wang, and Ong.[12] Work on single crystals and crystalline thin films by several groups has since established that at high temperatures the apparent lifetime separation extends over a wide range of doping;[3–10] the temperature dependence of ρ changes considerably, while that of $\cot \Theta_H$ retains its simple $A + BT^2$ form between T_c and approximately 200 K, as shown in Fig. 2.

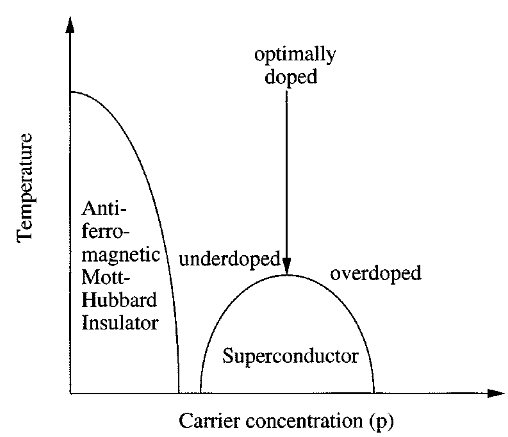

FIG. 1. An idealized phase diagram of the cuprate superconductors. The interplay between antiferromagnetism and superconductivity in the cross-hatched region is still uncertain. The range of doping covered by any material depends on details of the chemistry of the charge reservoir layers which supply carriers to the copper oxygen planes. For example, $YBa_2Cu_3O_{7-\delta}$ is ideal for studying the underdoped side, while $Tl_2Ba_2CuO_{6+\delta}$ is a clean material with long mean-free paths which allows investigation of the overdoped side. Qualitatively, the effect of correlations can be expected to weaken as the carrier concentration (p) increases. The size of the Fermi surface as a function of p remains a controversial issue.

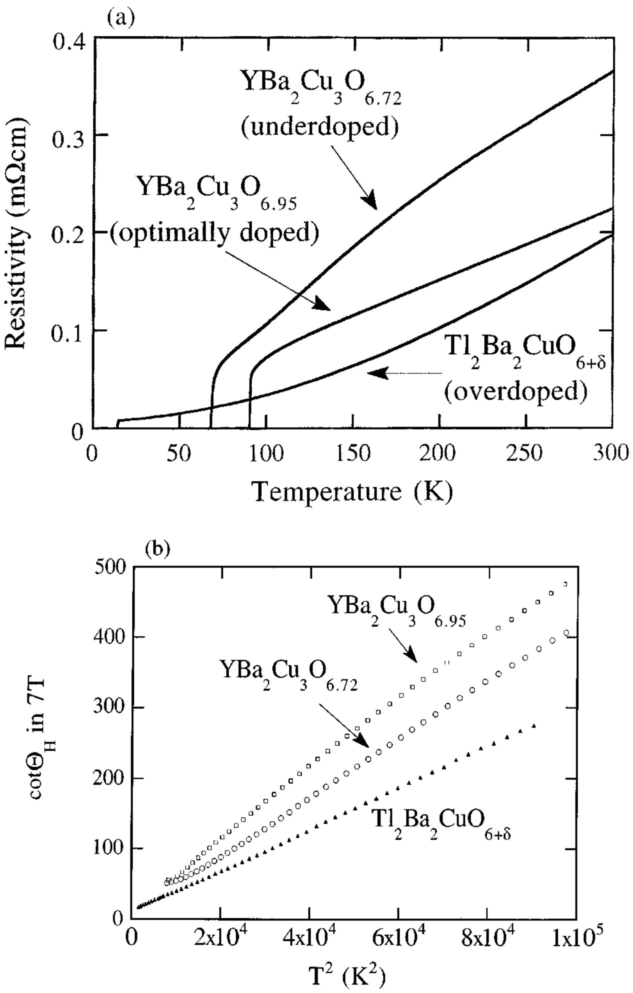

FIG. 2. Typical plots of the evolution of (a) the resistivity and (b) the cotangent of the Hall angle across the phase diagram. Although the temperature dependence of ρ changes considerably as a function of doping, work on single crystals and thin films shows that $\cot\Theta_H$ varies as T^2 below 200 K in almost every cuprate material. This suggests the existence of two distinct scattering rates in the normal-state physics of the cuprates. The $YBa_2Cu_3O_{7-\delta}$ data shown come from Ref. 4, but the figure is designed to be representative of an overall picture established by many groups (Refs. 3–10). In the overdoped sample of $Tl_2Ba_2CuO_{6+\delta}$ that is shown, a function of the form $A+BT+CT^2$ with an appreciable linear term is needed to fit $\rho(T)$, while $\cot\Theta_H(T)\sim A+CT^2$. In samples of $Tl_2Ba_2CuO_{6+\delta}$, the linear term becomes stronger as δ is decreased and T_c rises, until it dominates $\rho(T)$ when $T_c\sim 85$ K (Ref. 14). The smoothness of the progression, combined with the doping-independent $A+CT^2$ form of $\cot\Theta_H(T)$, is strong evidence that overdoped superconducting samples of $Tl_2Ba_2CuO_{6+\delta}$ have the essential normal-state features which are common to all the cuprates.

The doping level that can be achieved in any given material depends on details of the chemistry of its charge reservoir layers. In $YBa_2Cu_3O_{7-\delta}$, the available range of oxygen stoichiometry means that material can be prepared with doping anywhere between heavily underdoped (the antiferromagnetic insulator) and very slightly overdoped (fully oxygenated material). In the single crystals of $Tl_2Ba_2CuO_{6+\delta}$ which we have studied, there is a significant substitution of copper onto the thallium site,[13] which gives some intrinsic doping and means that varying the oxygen content produces material anywhere between optimally doped and heavily overdoped.[14] As the doping is increased the temperature dependence of the resistivity changes smoothly from linear in samples with $T_c=90$ K to one with considerably more curvature as T_c is reduced. If a variable power law of the form $A+BT^\alpha$ is used to fit the $\rho(T)$ data in samples with $T_c<20$ K, α exceeds the value of 1.5,[10] which has been suggested to be the limit in overdoped $La_{2-x}Sr_xCuO_4$.[15] In any superconducting sample, a weighted sum of T and T^2 terms of the form $A+BT+CT^2$ fits the resistivity data more satisfactorily than the variable power law, consistent with the linear T contribution persisting on the overdoped side of the phase diagram.[16] Also, the remarkable second lifetime seen in the Hall effect still exists in heavily overdoped material, suggesting that although the anomalous scattering which leads to the unique normal-state properties of the cuprates weakens as the doping is increased, it still plays an important role. Given its high purity (the mean-free path, ℓ, is of order 10^3 Å at low temperatures), $Tl_2Ba_2CuO_6$ is an excellent material in which to study the properties of the cuprate normal state.

Qualitatively, it is not very surprising that the normal-state properties begin to look more "standard" as the doping is increased, because the addition of carriers to the antiferromagnetic insulating state can be expected to weaken the strong correlations that exist there. The precise evolution of the normal-state physics is still controversial, however. Sketches like that shown in Fig. 1 are frequently used to describe the phase diagram of the cuprates, but they implicitly contain the assumption that the carrier concentration is linear in the chemical dopant concentration across the whole phase diagram. This implies a concentration of itinerant charge carriers in the range between 0 and 0.3 per copper atom and, in a naive picture, is equivalent to the existence of a Fermi wave vector $k_F<0.3$ Å^{-1}, a value far smaller than that predicted by band theory. While there is some evidence for this point of view from Hall effect measurements at low dopings and resistivity measurements in $La_{2-x}Sr_xCuO_4$ over a wider range of doping,[17] other normal-state probes such as angle-resolved photoemission spectroscopy (ARPES) seem to see a large Fermi surface which would correspond to a concentration of approximately 1.2 itinerant carriers per copper ($k_F\sim 0.7$ Å^{-1}) even in samples at optimum doping.[18] If this is correct, it seems likely that the "p" axis on sketches such as Fig. 1 is strongly nonlinear in the chemical concentration.[19] In most cuprates, the strong temperature dependence of R_H means that it is difficult to deduce k_F unambiguously from transport measurements.

The observation of a large "Fermi surface" by ARPES does not necessarily imply a Fermi-liquid ground state, and indeed the existing magnetotransport data are suggestive of a breakdown of Fermi-liquid theory such as that discussed in Ref. 11. However, other suggestions have also been made to account for the apparent lifetime separation seen in the transport properties. A strongly **k** dependent scattering rate having different temperature dependences on different parts of the Fermi surface can lead to an apparent separation,[5] although it is difficult to account for the extent of the separation seen in optimally doped materials in which ρ varies as $A+BT$ while $\cot\Theta_H$ varies as $A+BT^2$, both to high accuracy. A very square Fermi surface and a specific change of the scattering rate near the corners would be required. Another proposal is that the T^2 scattering rate probed by $\cot\Theta_H$ is evidence for Fermi-liquid behavior, and that the temperature dependences seen in ρ are due to a real temperature-dependent change in the carrier concentration which is accurately probed by $R_H(T)$.[20] Recently, it has also been suggested that the temperature dependence of the normal-state transport properties can be accounted for in terms of a single-component Bose fluid with boson localization playing an important role.[21] In this picture too, the temperature dependence of R_H reflects a real change in the concentration of itinerant carriers.

Overall, it seems that the existing high-temperature normal-state data are not sufficient to prove whether the normal state of the cuprates is a Fermi liquid or not. After all, Fermi-liquid theory is a low-temperature theory and to settle this issue conclusively it is necessary to have experimental data on normal-state properties in the low-temperature range. Non-Fermi-liquid temperature dependences caused by scattering from thermally excited bosons are commonplace, arising for example from phonons or spin fluctuations and in such cases the $T \rightarrow 0$ limit shows a crossover to Fermi-liquid power laws at some energy scale characteristic of the bosons.[22] The existence and value of such an energy scale in the cuprates could provide an important clue to their transport properties. Existing normal-state theories for the cuprates are implicitly based on the assumption that the high-temperature properties which can be measured can safely be extrapolated to give those that would exist at low temperatures if superconductivity did not intervene. It is not clear that this is the case; indeed, the power laws upon which so much reliance is placed may be affected by temperature-dependent changes to the sample volume in some materials at high temperatures.[23]

Although there is thus a need for precise low-temperature normal-state measurements on clean samples, they have not been possible until now because of the very high upper critical fields of most cuprate materials. In this respect, $Tl_2Ba_2CuO_{6+\delta}$ offers a new opportunity. Recently we showed that if single crystals are overdoped by incorporation of excess oxygen to reduce T_c to below 15 K, the critical fields are sufficiently reduced that the normal state can be accessed down to temperatures as low as 12 mK in magnetic fields of up to 18 T, while sample purity remains high with mean free paths of the order of 500–1000 Å at low temperatures.[24] In this paper, we present the results of a series of measurements on single-crystal samples with T_c in the range 10–16 K. Detailed measurements of the temperature dependence of both the normal-state resistivity and Hall effect at temperatures as low as 30 mK are presented. The low-temperature value of R_H, which is measured in the elastic scattering limit, allows us to estimate k_F as 0.7 Å^{-1}, corresponding to the existence of a large Fermi surface. However, non-Fermi-liquid power laws persist in the temperature dependences of the data down to at least $T<1$ K, with no clear evidence of a crossover to Fermi-liquid power laws to millikelvin temperatures, strongly suggesting the existence of a very low (perhaps zero) energy scale in the normal state. We discuss possible connections to the anomalous behavior previously reported in H_{c2}.

II. EXPERIMENTAL

The crystal growth, contact mounting, and sample characterization procedures used are outlined in Refs. 13 and 24. Crystals with $T_c<15$ K were prepared by annealing in flowing oxygen at 350 °C. When T_c is as low as this, it can be time dependent if the sample is left in a standard desiccator, presumably because the crystal contains more than its equilibrium oxygen content at room temperature. For this reason, the lowest T_c samples had to be stored at 200 K if there was a time delay of more than a few days between initial preparation and characterization and low-temperature study in the dilution refrigerator.

The most widely used procedure for Hall effect measurements at high temperatures is to isolate the odd component of the transverse voltage by turning the sample by 180° in a constant magnetic field, paying careful attention to temperature control. At low temperatures this would be very difficult, as friction effects would lead to large temperature rises with very long relaxation times. Instead, the measurements were performed using reversed field sweeps at constant temperature, monitoring the Hall signal and magnetoresistance (MR) simultaneously on different pairs of voltage contacts on the same sample with the magnetic field perpendicular to the a-b planes. There was no difficulty with possible thermometer magnetoresistance, as the thermometers are mounted in a field cancelled region, on the mixing chamber of the dilution refrigerator. The samples were thermally anchored to the mixing chamber by electrically grounding one of the current leads via an annealed silver wire.

A customized temperature control program gave a temperature stability of better than 1 part in 10^3 between 2 and 32 K, and better than 3 mK below 2 K, over the time (approximately 3 h) that it took to perform field-reversed sweeps between 0 and 16 T. Careful checks were performed at all temperatures to ensure that the sample and thermometer were in thermal equilibrium. Measurement currents of between 1 and 100 μA were used at various frequencies below 25 Hz. Higher temperature measurements were performed in standard continuous flow ^{4}He cryostats in magnetic fields of up to 8 T, using equipment and methods similar to those reported in Refs. 4 and 5.

An example set of raw data from a run at 18 K is shown in Fig. 3. At lower temperatures the traces are cut off at low fields by the appearance of superconductivity, but in this sample there is always a normal-state region between 14 and 16 T at temperatures above 30 mK. As can be seen from Fig. 3, there is a very slight deviation from linearity of the Hall voltage as a function of magnetic field at high fields. This deviation decreases as the temperature is reduced, and it was possible to extract the genuine low-field Hall coefficient at all temperatures studied. The Hall effect data from one sample (sample A) are shown and discussed throughout this paper, but all the basic features reported here were also seen in repeat measurements on two additional samples. In addition, detailed ρ-T measurements were performed on a fourth sample with a lower T_c of approximately 11 K (sample B). H_{c2} is a strong function of T_c in $Tl_2Ba_2CuO_{6+\delta}$, and so the normal state was available over a wider range of magnetic fields in this sample.

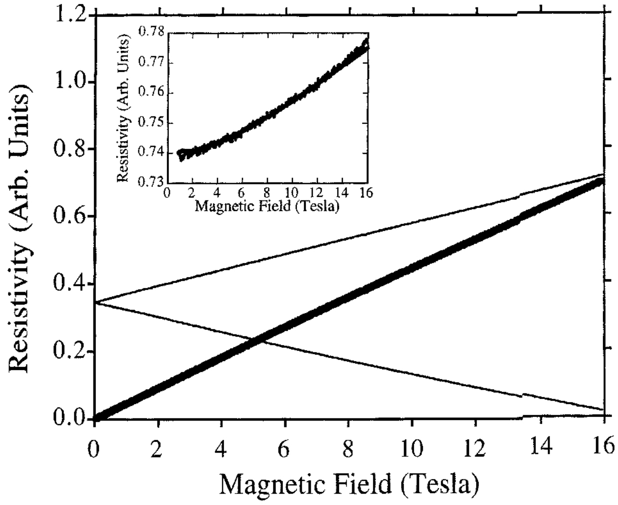

FIG. 3. Raw resistance data from a pair of Hall effect contacts at 18 K (above the T_c of 15 K of this sample). The thin lines show the field dependence of the voltage as the field is swept to 16 T in either magnet polarity. The resistance in zero field is the small out of balance signal which is always present in Hall effect measurements on crystals. The thick trace is the Hall signal, obtained by subtracting the raw data from the reversed field sweeps. It is linear in field at low fields. Inset: The transverse magnetoresistance (MR) data obtained by adding the raw data, superimposed on the MR data obtained from a longitudinal pair of contacts in both field directions. Taken together, these data show that the current paths in the sample are homogeneous, and that this method of measuring the Hall effect is reliable. The temperature drift during the three hours that it took to acquire the data was 6 mK.

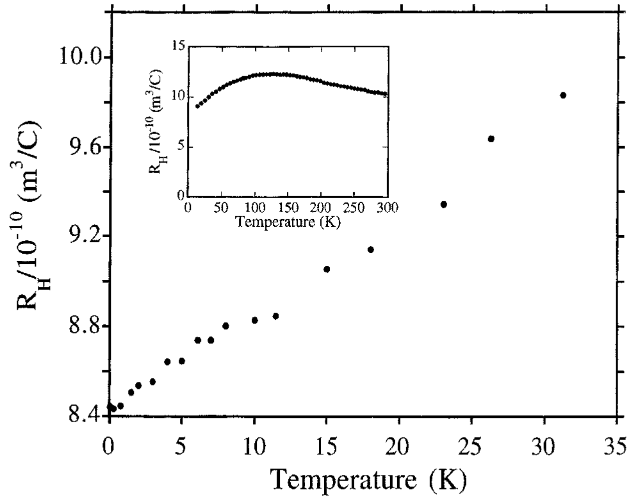

FIG. 4. The weak, almost linear, low-temperature dependence of the Hall coefficient R_H, which is seen to be a smooth extrapolation of the high-temperature data shown in the inset. The low-temperature behavior is not consistent with any model in which the temperature dependence of R_H is exclusively due to a real temperature-dependent change in the carrier concentration, as this would require that in the $T \rightarrow 0$ limit the carrier concentration increases as the temperature falls.

III. RESULTS AND DISCUSSION

A. Hall coefficient temperature dependence

The low-temperature behavior of the Hall coefficient, R_H, is shown in Fig. 4. In the inset, we show high-temperature data between 30 and 300 K, which are similar to those reported in Ref. 10. The broad maximum at approximately 100 K has been seen in many other cuprate materials. Our low-temperature data show that below the maximum, R_H continues to fall steadily with decreasing temperature, with no saturation down to the lowest temperatures reached. This observation is incompatible with simplified pictures in which a temperature-dependent R_H is taken to indicate a real change in the carrier concentration, because this would require the carrier concentration to *rise* with decreasing temperature below 10 K.

B. Magnetoresistivity

As can be seen from the inset to Fig. 3, we observe a small positive magnetoresistance (MR). Its magnitude varies from sample to sample, with $\Delta\rho/\rho$ lying between 0.04 and 0.1 at 16 T and 18 K. The field dependence is slightly unusual. Even at 32 K, our highest temperature in the experiment to 16 T, $\Delta\rho$ varies strictly as B^2 only for $B<4$ T, with the field dependence becoming shallower at higher fields. As the temperature is lowered the deviations begin at lower fields and below T_c superconductivity intervenes at low field making it impossible to observe the strictly B^2 part. We believe that this may be due to our working in the intermediate field regime at these low temperatures, because in these samples $\omega_c\tau>0.1$ at 16 T below 50 K. As the temperature is increased the resistivity increases rapidly and the B^2 field dependence of the MR persists to higher fields. A fuller account of the MR in $Tl_2Ba_2CuO_{6+\delta}$ up to 300 K will be published separately.[25]

C. Temperature dependence of resistivity

Expressed as a fraction of the total resistance, the temperature dependence of the high field MR is very small at low temperatures,[26] meaning that the temperature dependence of the resistivity can be studied to high accuracy by considering data at a fixed value of the magnetic field. The resistivity at 16 T of the crystal for which the Hall effect data are shown in Figs. 2 and 4 is plotted as a function of temperature below 6 K in Fig. 5. Although a Fermi-liquid-like $A+BT^2$ dependence might have been expected at low temperatures in samples of this doping, we observe the opposite, with *low* power terms remaining strong as the temperature drops below 10 K. If a fit of the form $A+BT+CT^2$ is performed on the data, the strength of the linear term is similar (within a factor of 2) whether data sets between 0 and 6 K or 20 and 200 K are used, so it seems that the linear term persists to low temperature. Its magnitude is weaker than that found in optimally doped material (by a factor of 10–15), but this might be expected given the smooth evolution of the normal-state properties as a function of doping. Recently $\rho(T)$ has been studied to below 1 K in underdoped $La_{2-x}Sr_xCuO_4$ using a 62 T pulsed field to suppress the superconductivity.[27] In that material ρ diverges logarithmically at low temperatures in contrast to our observation of metallic behavior all the way down to 30 mK.

The data shown in Fig. 5 were constructed from a series of sweeps of the magnetic field which were performed over a

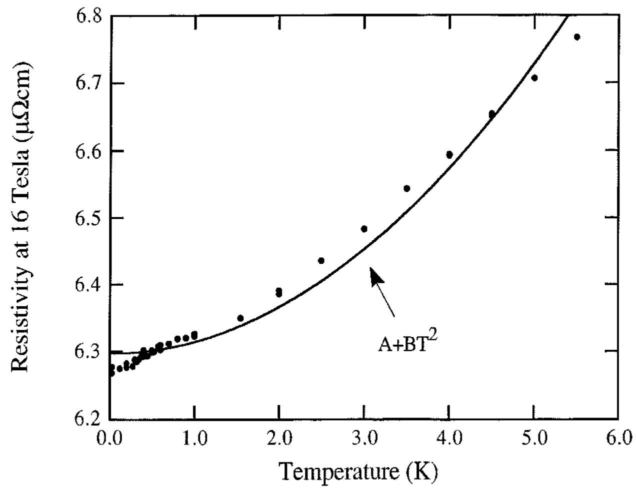

FIG. 5. The $A+BT^2$ temperature dependence expected of a Fermi liquid is not seen in the low-temperature range, at least to below 1 K, where the data become somewhat ambiguous.

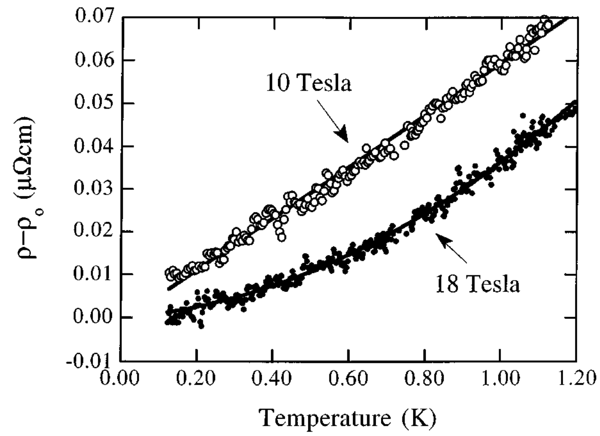

FIG. 7. The temperature dependence of ρ for sample B below 1.2 K in fields of 10 and 18 T, at a sweep rate of 8 mK/min. In this temperature range, small field dependent changes to the curvature of ρ are seen, with more curvature at the higher field.

period of several weeks, and the scatter seen is more a reflection of the long-term stability of the current generator and readout electronics than of the intrinsic noise levels of the data acquisition system. In addition to this, the H_{c2} value of the crystal was sufficiently large that the normal state could be studied to low temperatures only at 16 T or above. We therefore decided to check the existence of the low-power term by performing temperature sweeps at a series of fixed magnetic fields on a crystal (sample B) with a lower T_c (11 K) and H_{c2} ($\sim$6 T at 20 mK). The results of temperature sweeps between 1 and 5 K at fixed magnetic fields of 8 and 16 T are shown in Fig. 6 and it can be seen that the temperature dependence, containing the strong linear term, is essentially identical over this field range. The temperature dependence has a slight field dependence below 1 K, however. Detailed data between 120 mK and 1.2 K are shown in Fig. 7. At 10 T they are almost perfectly linear all the way down to 120 mK, but by 18 T more curvature has developed, and the data are consistent with an $A+BT^2$ dependence over this fairly narrow temperature range. Other runs at 8, 12, 14, and 16 T (not shown) confirm that there is a smooth crossover between the two types of behavior.

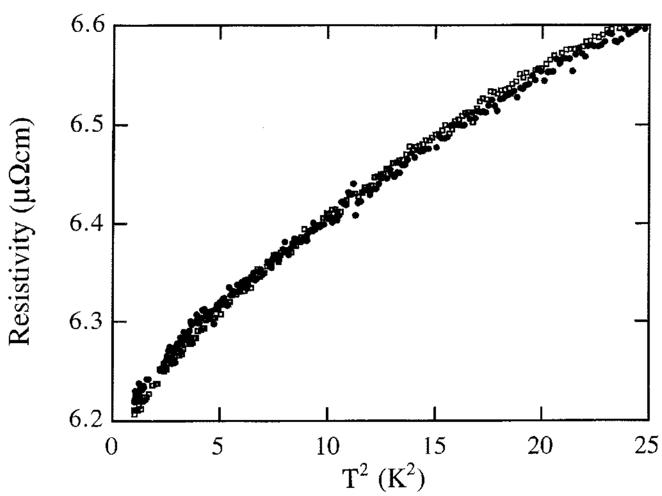

FIG. 6. The temperature dependence of ρ for a second sample (B) with a lower T_c of 11 K measured by sweeping the temperature at 20 mK/min between 1 and 5 K in fixed field. Data at 8 and 16 T are shown, plotted against T^2. A small temperature-independent MR difference of approximately 0.35 $\mu\Omega$ cm has been subtracted from the 16 T data to allow the two sets of data to be plotted together. These data confirm that the temperature dependence of the MR is very weak, and again show a strong linear in T term, very similar to that seen in the data from sample A.

In a recent paper, Hlubina and Rice have emphasized that an $A+BT^2$ dependence of ρ might be preserved even in materials in which the scattering rate is non-Fermi-liquid-like over most (or in some cases all) of the Fermi surface.[28] In light of this the observation of a strong linear term persisting to such low temperatures gives strong evidence that this heavily overdoped cuprate is a very unusual metal indeed.

The data shown in Fig. 7 might be interpreted in terms of quantum critical point theory. If the quantum critical point is caused by T_c being depressed to zero by the magnetic field, a linear term in ρ persisting to the lowest temperatures may be expected at fields slightly higher than H_{c2}. In practice this seems to occur up to approximately $2H_{c2}$. At higher fields than this, as we move away from the critical point in the H-T plane, a T^2 term is restored at the lowest temperatures. This is only one interpretation, however, and care must be taken in interpreting conductivity data near a *superconducting* quantum critical point (as opposed to one which is magnetic in origin, for example). Study of more samples is desirable, as there is always the more mundane possibility of spurious sample-dependent superconductivity above what appears to be H_{c2} affecting data at this very fine level of detail.

D. Hall Angle

The temperature dependence of the cotangent of the Hall angle ($\cot\Theta_H=\rho/R_HB$) is shown in Figs. 8 and 9. In spite of the fact that $\cot\Theta_H$ varies almost perfectly as $A+BT^2$ between 30 K and room temperature, as shown in Fig. 2 and the inset to Fig. 8, it deviates significantly from this temperature dependence below 25 K and particularly below 10 K. In

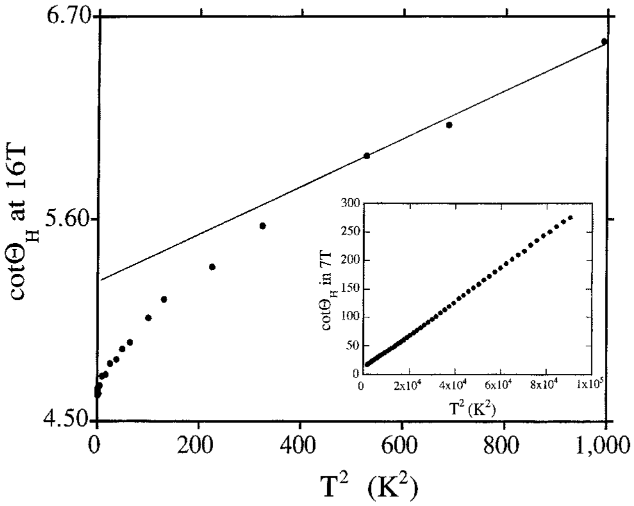

FIG. 8. The cotangent of the Hall angle plotted against T^2 below 30 K. The low-temperature data deviate significantly from the $A+BT^2$ dependence seen at high temperatures (inset), whose extrapolation is shown by the solid line.

fact, if ρ and $\cot\Theta_H$ are plotted together on linear axes, as in the main part of Fig. 9, their basic temperature dependence is seen to be almost identical at low temperatures. The high-temperature ρ and $\cot\Theta_H$ data of Fig. 2 are replotted in the inset on linear axes to show the different behavior that is observed between 30 and 300 K, where the commonly observed lifetime separation discussed in the introduction still holds. In one sense the low-temperature properties look less

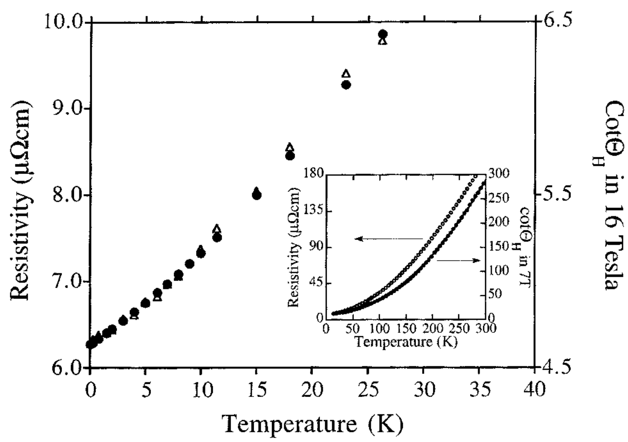

FIG. 9. The cotangent of the Hall angle and the resistivity plotted on linear axes in the low-temperature and (inset) high-temperature regimes. The high-temperature data for $\cot\Theta_H$ vary as $A+BT^2$ to high accuracy, and clearly have a different temperature dependence from the resistivity, indicating that the lifetime separation seen almost universally at high temperatures in the cuprates is also present in this sample. At low temperatures, the lifetime separation has disappeared, reminiscent of the situation in a more standard metal, *except* that ρ and $\cot\Theta_H$ both show a non-Fermi-liquid temperature dependence. The high-temperature data are for a 7 T field, and the low-temperature data for a 16 T field, to ensure that the normal state is reached even at the lowest temperatures. The temperature dependence observed between 1 and 35 K is independent of the choice of field between 7 and 16 T.

anomalous than the high-temperature ones, since the lifetime separation has collapsed, but instead of ρ becoming more T^2-like at low temperatures, $\cot\Theta_H$ has lost its "Fermi-liquid" T^2 dependence and assumed a lower power as the temperature has dropped below 10 K.

E. Hall coefficient Fermi surface size

There is a further advantage in measuring the Hall effect down to such low temperatures. The inelastic processes which lead to the strong temperature dependence of R_H in most cuprate materials may be **k** dependent, and so it has always been difficult to extract a reliable value for the carrier concentration from transport measurements. If the charge dynamics are explained in a spin-charge separation model. $R_H \sim \tau_H/\tau_{\rm tr}$ at high temperatures, and similar difficulties exist. At $T\sim 0$, however, we are in the elastic-scattering limit, and experimentally we see a collapse of the lifetime separation in this regime, so the in-plane mean-free path can be taken to be isotropic to a good approximation. If, as seems reasonable, a nearly circular Fermi surface is assumed for this heavily overdoped material. R_H in this limit gives an accurate estimate of the carrier concentration even for measurements in the weak field regime.[29] Our measured value of $\sim 8.5\times 10^{-10}$ m^3/C corresponds to ~ 1.3 itinerant holes per copper atom, or a "large" k_F of ~ 0.7 Å^{-1}.

In many cuprates, R_H has a maximum similar to that shown in the inset to Fig. 4, and is decreasing, sometimes quite rapidly, in the lower temperature region before being cutoff by T_c. In $Bi_2Sr_2CuO_6$, for example, R_H has been studied down to temperatures as low as 15 K in a sample with a linear resistivity which is presumably close to optimum doping.[30] If, as seems likely, the R_H data extrapolate to $T=0$ in the manner seen here in $Tl_2Ba_2CuO_{6+\delta}$, this would correspond to a k_F of ~ 0.6 Å^{-1}. It would be very interesting to perform similar low-temperature Hall effect measurements on this material and others from the underdoped side of the phase diagram.

IV. CONCLUSIONS

Our observations suggest that the ground state of $Tl_2Ba_2CuO_{6+\delta}$ is not a conventional Fermi liquid, even though we infer a value of k_F which is consistent with a large Fermi surface. The significance of the unusual low-temperature power laws that we have observed is emphasized by a comparison with the properties of Sr_2RuO_4, which is a layered perovskite superconductor with a low superconducting transition temperature of approximately 1 K.[31] The Fermi-liquid ground-state of Sr_2RuO_4 has been established by detailed measurements of quantum oscillations in its resistivity and magnetic susceptibility,[32] and below 30 K, ρ varies as $A+BT^2$ to high accuracy,[33] in sharp contrast to the present observations.

The resistivity and Hall effect data on $Tl_2Ba_2CuO_{6+\delta}$ strongly suggest the existence of a very low energy scale which is playing an important role in determining the normal-state physics. It is tempting to suggest that the same scale is involved in the anomalous behavior seen in H_{c2} in similar samples. Near T_c, $H_{c2}(T)$ varies linearly as $1-T/T_c$, but below about 10 K it rises sharply with strong positive curvature. This 10 K energy scale is very similar to that which affects $\cot\Theta_H$ (Fig. 8), so H_{c2} could well be a sensitive probe of anomalous normal-state behavior.

The collapse of the lifetime separation at low temperatures seen in Figs. 8 and 9 does not rule out the possibility of spin-charge separation, and may be explicable in this class of theory as a consequence of entering a regime dominated by elastic scattering.[34] In contrast, the observation that R_H increases linearly with T at low temperatures is surely strong evidence against pictures which propose that $R_H(T)$ probes a real change in the carrier concentration, as the number of carriers would be required to *increase* with decreasing temperature in the range below 30 K.

In summary, we have studied the magnetotransport properties of heavily overdoped $Tl_2Ba_2CuO_{6+\delta}$ down to the millikelvin temperature range, and have established the existence of a large Fermi surface in this cuprate material. We observe non-Fermi-liquid-like power laws in the transport coefficients in a similar temperature range to anomalous behavior previously reported in H_{c2}. The data clearly show that a very low energy scale is playing an important role in the physics of $Tl_2Ba_2CuO_{6+\delta}$.

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