Breakdown of Fermi-liquid theory in a copper-oxide superconductor

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The behaviour of electrons in solids is well described by Landau's Fermi-liquid theory, which predicts that although electrons in a metal interact, they can still be treated as well defined fermions, which are called 'quasiparticles'. At low temperatures, the ability of quasiparticles to transport heat is given strictly by their ability to transport charge, as described by a universal relation known as the Wiedemann–Franz law, which hitherto no material has been known to violate. High-temperature superconductors have long been thought to fall outside the realm of Fermi-liquid theory, as suggested by several anomalous properties, but this has yet to be shown conclusively. Here we report an experimental test of the Wiedemann–Franz law in the normal state of a copper-oxide superconductor, $(Pr,Ce)_2CuO_4$, which reveals that the elementary excitations that carry heat in this material are not fermions. This is compelling evidence for the breakdown of Fermi-liquid theory in high-temperature superconductors.

Landau's Fermi-liquid theory is the definitive theory of electrons in metals[1], or more generally fermions in condensed matter, and is a major landmark of twentieth-century physics. For example, it is the necessary foundation for the theory of superconductivity by Bardeen, Cooper and Schrieffer (BCS)[2]. In essence, it says that even in the presence of interactions the low-energy excitations of a system of mobile fermions can still be described in terms of well defined fermionic particles, called 'quasiparticles', with charge e, spin 1/2 and a mass m^*, the latter being renormalized by interactions. The Wiedemann–Franz (WF) law is one of the basic properties of a Fermi liquid, reflecting the fact that the ability of a quasiparticle to transport heat is the same as its ability to transport charge, provided it cannot lose energy through collisions. Reported[50] as an empirical observation by Wiedemann and Franz in 1853, the law states that the heat conductivity κ and the electrical conductivity σ of a metal are related by a universal constant:

$$\frac{\kappa}{\sigma T} = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2 \equiv L_0 \qquad (1)$$

where T is the absolute temperature, k_B is Boltzmann's constant and $L_0 = 2.45 \times 10^{-8}\,\mathrm{W\,\Omega\,K^{-2}}$ is Sommerfeld's value[3] for the Lorenz ratio, $L \equiv \kappa/\sigma T$.

The linear power of temperature in equation (1) comes from the linear temperature dependence of the fermionic specific heat, through the relation between heat transport and heat capacity. In kinetic theory,

$$\kappa = \frac{1}{3} cvl \qquad (2)$$

where c is the specific heat of the carriers, v is their average velocity and l their mean free path. Provided the mean free path between collisions is independent of temperature, as it is for the strictly elastic processes that operate at $T \to 0$, the heat conduction has the same T dependence as the specific heat. So for electrons, it is also linear in T, and given by equation (1). By contrast, boson-like excitations such as phonons or magnons give rise to a low-temperature specific heat and a heat conductivity as $T \to 0$ which are both proportional to T^3.

Theoretically, electrons are predicted to obey the WF law at $T \to 0$ in a very wide range of environments[4]: in both three dimensions or two dimensions (but not strictly in one dimension), for any strength of disorder and interaction (in the scaling theory of disorder and interaction)[5], scattering[6] and magnetic field[7]. Experimentally, the WF law does appear to be universal at $T \to 0$: no materials have been reported to violate it. (We note that a departure from equation (1) has in fact been reported for silver[8], but is in contradiction with other measurements; refs 9, 10, and R.W.H. and E. Boaknin, unpublished results). This is true not only of simple metals like copper[9,10], but also of systems with strong electron correlations—such as the heavy fermion compounds $CeAl_3$ (ref. 11), $CeCu_6$ (ref. 12) and UPt_3 (ref. 13)—or with highly anisotropic conduction—such as the quasi-two-dimensional system Sr_2RuO_4 (ref. 14) (a ruthenate which is isostructural to the cuprate La_2CuO_4), the quasi-one-dimensional organic conductor $(TMTSF)_2ClO_4$ (ref. 15) or the two-dimensional electron gas in a MOSFET[16]. Even in the presence of so-called non-Fermi-liquid behaviour, where the electrical resistivity is seen to deviate from the standard T^2 dependence, the WF law still holds at $T \to 0$, as observed in $CeNi_2Ge_2$ (ref. 17). All this strongly suggests that the ground state of every metal investigated thus far is a Fermi liquid. Of course, if the metallic state gives way to a superconducting state at low temperature, then the WF law is entirely violated, as the charge is no longer transported by fermions but by Cooper pairs, which carry no entropy.

In 1986, high-temperature superconductivity was discovered in a class of copper oxides, and fifteen years hence the fundamental question about these materials still remains: are they host to a new state of matter? In particular, are they Fermi liquids in their ground state, once superconductivity is removed (either by application of a magnetic field or by doping)? Anderson[18] proposed early on that the copper oxides are indeed fundamentally different from other metals in that they are Mott insulators. When a small number of electrons or holes are doped into the CuO_2 planes of their crystal structure, these materials can conduct charge reasonably well and also form a superconducting state. It is believed that the basic excitations of a doped Mott insulator are not fermionic quasiparticles as in other metals—with charge, spin and heat all carried by one and the same particle. Instead, the electron is thought to 'fractionalize' into a neutral spin-1/2 fermion called a 'spinon' and a spinless charge-e boson called a 'holon', or a 'chargon', a phenomenon usually called 'spin–charge' separation[19].

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Even though this bold proposal for a fundamentally new state of matter continues to be at the heart of several current theories of the copper oxides (ref. 20 and references therein), there has been little experimental evidence for such spin–charge separation. On the contrary, for example, a BCS/Fermi-liquid theory of *d*-wave quasiparticles appears to work rather well in the superconducting state of hole-doped copper oxides, at least at low energy and near optimal doping[21]. Conceptually, a simple way to investigate the possibility of spin–charge separation is to measure the properties of charge transport and compare them to those of either spin or entropy transport.

Here we report on the first test of this kind, where both the charge conductivity σ and the heat conductivity κ of a copper oxide superconductor are measured in the normal state at $T \rightarrow 0$. We observe a good, metallic-like nearly temperature-independent charge transport at low temperature without the corresponding heat transport expected for the WF law. The normalized Lorenz number L/L_0 goes from being much less than unity at $T \rightarrow 0$ to being greater than unity above 0.2 K. This strongly suggests spin–charge separation and is a compelling demonstration that the ground state of copper oxides can fall outside the realm of Fermi-liquid theory.

The material

The copper oxide material used for this study is $Pr_{2-x}Ce_xCuO_{4-y}$ (PCCO), with a doping concentration of $x = 0.15$, which is roughly the optimum value for maximizing the transition temperature for superconductivity, where $T_c \approx 20$ K. The addition of x Ce atoms on Pr sites adds x electrons to the CuO_2 planes of the parent insulating compound, the Mott insulator Pr_2CuO_4. PCCO is the electron-doped analogue of the hole-doped material $La_{2-x}Sr_xCuO_{4-y}$ (LSCO), wherein the addition of x Sr atoms on La sites removes x electrons from (adds x holes to) the CuO_2 planes. In LSCO, the optimum doping is also at approximately $x = 0.15$, with a maximum $T_c \approx 40$ K. For reasons that are not clear, both materials have critical temperatures that are significantly lower than that of several other copper oxides, such as $YBa_2Cu_3O_{7-\delta}$ (Y-123), $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) and $Tl_2Ba_2CuO_{6+\delta}$ (Tl-2201), which all have a maximum T_c around 90 K. Nevertheless, all copper oxides share the same basic crystal structure, namely that of a stack of CuO_2 planes, and the same generic dependence on doping. The technical advantage of LSCO and PCCO is that the magnetic field needed to destroy superconductivity is correspondingly lower, with upper critical field values of ~50 T and ~10 T, respectively. Since these fields can be achieved in the laboratory, it is possible to investigate their low-temperature transport properties in the normal state, such as was done for charge conductivity on LSCO[22] and on PCCO[23].

Crystals

The single crystal of PCCO used in this study was grown with a flux technique described elsewhere[24,25], using an Al_2O_3 crucible and an oxygen reduction treatment at 1,000 °C. The concentration of Ce was fixed at $x = 0.15$. Contacts were made with silver epoxy, diffused at 500 °C for 1 hour, and were used to measure both electrical resistivity and thermal conductivity. The electrical resistance of contacts was typically ~1 Ω. The crystal was in the shape of a platelet, 37 μm thick and 720 μm wide, with 1.0 mm separation between voltage contacts. The superconducting transition temperature T_c was obtained from three different measurements: at the end of the drop in resistivity, at the end of the diamagnetic drop in susceptibility and at the onset of a small peak in thermal conductivity. In all cases, $T_c = 20$ K to within less than $\pm$ 0.5 K. The width of the transition is 6 K in resistivity, 3 K in magnetization and about 1 K in thermal conductivity. The broad resistive transition, seen both as a function of temperature and magnetic field, is most probably due to an inhomogeneous distribution of oxygen near the surface. The much narrower transition obtained in thermal conductivity shows that this inhomogeneity is confined to a negligible volume of the sample, and therefore does not affect bulk measurements such as heat transport. We note that all results presented in this paper were reproduced on several other single crystals grown in similar conditions, with comparable T_c and resistivity.

Charge transport

The temperature dependence of the electrical resistivity, ρ, is shown in Fig. 1 for different magnetic fields applied parallel to the *c* axis of the tetragonal crystal structure. The current is made to flow in the CuO_2 planes, where the conduction is some 10^4 times better than perpendicular to the planes (at room temperature). Above 25 K, the temperature dependence $\rho(T)$ is not linear as in most optimally doped copper oxides, but follows a power law $a + bT^{\alpha}$ with $\alpha \approx 1.7$, and has a magnitude characteristic of a reasonably good metal: $a \approx 25$ μΩ cm and $\rho(300\ \text{K}) \approx 140$ μΩ cm. The effect of a magnetic field is rapidly to suppress the superconducting transition initially, but then more slowly at high fields, giving rise to a curve $T_c(H)$ that has strong positive curvature. From the magnetoresistance at 0.3 K shown in Fig. 1, lower inset, we can see that the entire sample has completed its transition to the normal state by 13.5 T. However, the bulk of the sample is no longer superconducting above 8 T, the field beyond which the low-temperature heat transport ceases to evolve (see Fig. 2).

The overall behaviour of the resistivity in PCCO is similar to that of hole-doped copper oxides when overdoped. Indeed, when doped to have a T_c of 15 K, Tl-2201 has a resistivity which grows as $T^{1.75}$ with values of 10 μΩ cm at low temperature and 180 μΩ cm at room temperature, and a resistive critical field with a strong upward curvature reaching a value of 16 T at $T \rightarrow 0$ (ref. 26). One difference is the slight upturn seen at low temperature in PCCO and not in Tl-2201. The resistivity in the normal state (at 14 T) increases by about 10% in going from 8 K down to 0.3 K (see Fig. 1). Similar but much larger upturns were observed in $Nd_{2-x}Ce_xCuO_4$ (NCCO)[27,28] and PCCO[25] at lower carrier concentrations; these were attributed to weak localization. In support of this interpretation is the suppres-

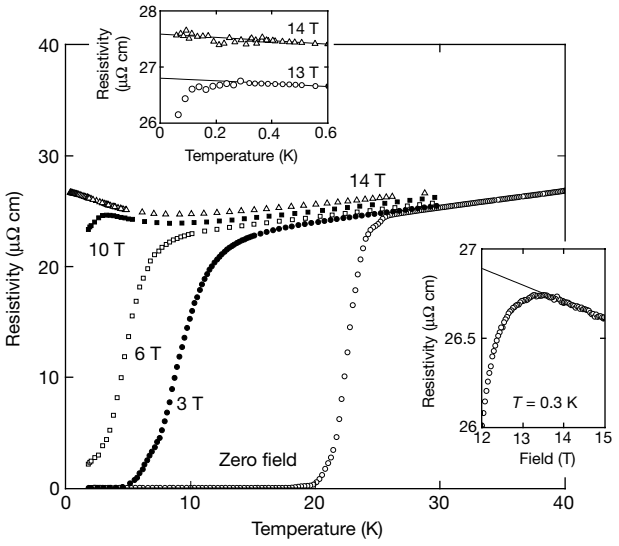

Figure 1 Electrical resistivity of PCCO versus temperature for a current in the basal plane at different values of magnetic field applied normal to the plane. Upper inset, zoom of low-temperature dependence at 13 T and 14 T, the latter being shifted upwards by 0.8 μΩ cm for clarity. Lines are linear fits to the data below 1.0 K. Lower inset, resistivity versus magnetic field at $T = 0.3$ K, showing that the crystal has fully completed its transition to the normal state by 13.5 T. The line is a linear fit to the negative magnetoresistance between 13.5 and 15 T.

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sion of the upturn by a transverse magnetic field, also observed in our samples (see lower inset of Fig. 1). This negative magnetoresistance eventually flattens to a constant beyond 25 T, equal to 25.2 μΩ cm at 0.5 K (R.W.H., unpublished results).

Thus, once the superconducting order has been completely suppressed throughout the sample, namely in a magnetic field larger than 13.5 T, the charge transport of this copper-oxide material at low temperature is that of a fairly good quasi-two-dimensional metal, with a residual resistivity $\rho(T \to 0) = \rho_0 = 26.8\ \mu\Omega$ cm in 14 T, which corresponds to a conductivity per CuO_2 plane of 60 e^2/h (that is, $k_F l \approx 60$).

Heat transport

Fifteen years after the discovery of high-temperature superconductivity, very little is known about the normal state of copper oxides at low temperature. The ability to suppress superconductivity in optimally doped PCCO with a field of only 14 T provides a rare opportunity to shed light on the fundamental nature of the electron system in these materials. We did this by measuring the transport of heat as $T \to 0$. The thermal conductivity $\kappa(T)$ of PCCO is shown in Fig. 2 at temperatures below 0.2 K, for heat flowing parallel to the CuO_2 planes. The data is plotted as κ/T versus T^2 in order easily to separate the contributions of phonons and electrons, using the fact that phonons are expected to have a heat conductivity which varies as T^3 when their mean free path reaches the size of the crystal at sufficiently low temperature. A straight line extrapolating to zero in κ/T versus T^2 is indeed the asymptotic ($T \to 0$) behaviour observed in insulators[29], including the Mott insulator $YBa_2Cu_3O_6$ (that is, Y-123 without any doped carriers)[30]. This is also the behaviour of conventional (*s*-wave) superconductors. The absence of a residual linear term κ_0/T, defined as the value of κ/T as $T \to 0$, means that there are no mobile fermionic excitations at low temperature. In insulators, this is owing to the lack of electronic carriers, while in superconductors it is because electrons have all formed Cooper pairs at $T \ll T_c$. The heat is then conducted entirely by phonons. In contrast, a residual linear term is observed when fermionic excitations are present, as in the following three instances: (1) in metals, with a residual linear term given precisely by the WF law; (2) in the vortex state of *s*-wave superconductors, where a magnetic field induces a residual linear term by generating delocalized quasiparticles[31]; and (3) in *d*-wave superconductors, where zero-energy quasiparticles are induced by impurity scattering[32].

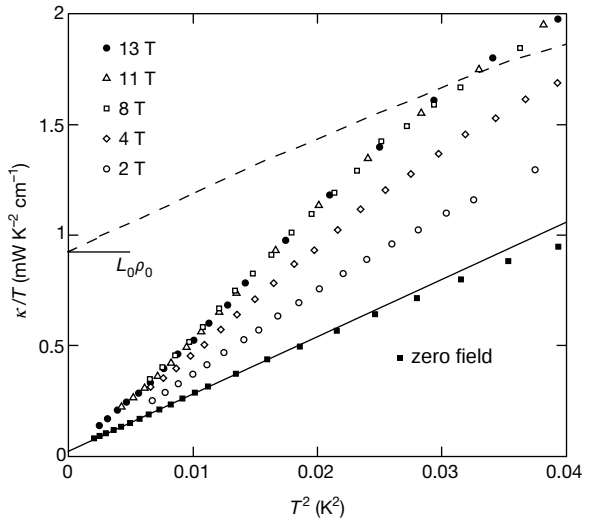

Figure 2 Thermal conductivity of PCCO for a heat current in the basal plane, plotted as κ/T versus T^2, at different values of the magnetic field applied normal to the plane. The solid line is a linear fit to the zero-field data below 130 mK. The dashed line shows the behaviour of a Fermi liquid with the residual resistivity ρ_0 of this sample, calculated as the sum of a constant electronic linear term via equation (1) and a phonon conductivity given by the solid line (zero-field data).

Superconducting state

In the absence of a magnetic field, there is only a very small residual linear term in the thermal conductivity of PCCO. From data on four different crystals, we find $\kappa_0/T = 0.03$–0.07 mW K^{-2} cm^{-1}. This is considerably smaller than the residual linear term observed in three hole-doped copper oxides, at optimal doping: $\kappa_0/T = 0.14$, 0.15 and 0.11 mW K^{-2} cm^{-1}, in Y-123 (refs 30, 33), Bi-2212 (refs 34, 35) and LSCO[36], respectively. Within BCS theory applied to a *d*-wave superconductor, this fermionic residual heat conduction is expected, arising from zero-energy quasiparticles induced by impurity scattering near the nodes in the $d_{x^2-y^2}$ gap function[32]. In the case of Bi-2212, the excellent quantitative agreement between theory and experiment has been viewed as a strong validation of Fermi-liquid quasiparticle theory for the superconducting state[21,34], at least at optimal doping and low energies.

Several tentative explanations may be offered for the weakness of a residual linear term in PCCO. The first possibility is the localization of *d*-wave quasiparticles (ref. 37 and references therein). It was invoked recently as a possible cause for the absence of a residual linear term in $YBa_2Cu_4O_8$ (Y-124)[38]. However, it is not clear why localization should occur in Y-124 and not in Y-123, given that these two copper oxides have comparable structure and properties. It seems more plausible in PCCO, because of the highly two-dimensional nature of its conduction—some 100 times more anisotropic than either Y-124 or LSCO. On the other hand, Bi-2212 is equally anisotropic, yet shows delocalized quasiparticles. A second possibility is the absence of nodes in the gap structure of PCCO. This would eliminate any residual linear term (at least in zero magnetic field). The symmetry of the order parameter need not be *s*-wave, but could have the form $d + ix$, where x is a subdominant component of either *s* or d_{xy} symmetry. The possibility of a $T = 0$ transition in the order parameter from *d* to $d + ix$ as a function of doping has been raised in the context of a possible quantum critical point in the phase diagram of copper oxides[39]. For PCCO, however, this would seem to be in conflict with evidence for a rather pure $d_{x^2-y^2}$ symmetry, as determined in a recent tricrystal experiment[40]. The other difficulty is that, as we shall see below, a magnetic field normal to the CuO_2 planes never induces a residual linear term, implying that the minimum gap would have to be a sizeable fraction of the maximum gap (that is, x comparable to d). This would have to be reconciled with the penetration depth data[41,42]. A third possibility[43], is the removal of the nodes as a result of static stripe ordering.

Normal state

As seen in Fig. 2, the basic effect of a magnetic field is rapidly to increase the thermal conductivity of PCCO (at finite temperature). Given that the phonon conductivity cannot exceed its value at zero field (where the phonon mean free path has reached its maximum value), this increase must be due to excitations of electronic origin. The field-induced conduction (over and above the zero-field curve) grows rapidly, and approximately linearly, with magnetic field at low fields, and eventually saturates at high fields, where κ is absolutely constant above 8 T. This is compelling evidence that the thermodynamic upper critical field in this sample is at most 8 T and the bulk of the crystal is in the normal state beyond that. Indeed, in all known superconductors, whether *s*-wave or *d*-wave, the electronic thermal conductivity is always affected by the magnetic field when in the vortex state and seen to saturate above H_{c2} (see for example ref. 44). Such an H_{c2} agrees reasonably well with the criterion of zero resistance, achieved at about 6 T, and also agrees with the H_{c2} values reported previously in thin films of PCCO[23,45] and NCCO[45,46] at $x = 0.15$. A roughly linear growth of κ with magnetic field is also what is seen in the borocarbide superconductor $LuNi_2B_2C$ (ref. 31), but with an important difference: in

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$LuNi_2B_2C$, the field induces a linear term at $T \rightarrow 0$. Furthermore, this finite residual linear term ultimately reaches a value in the normal state given precisely by the WF law. In striking contrast, a magnetic field, even as high as 13 T, almost twice H_{c2}, never induces a residual linear term in PCCO. Given the known value of the electrical resistivity at $T \rightarrow 0$ and 13 T, namely $\rho_0 = 26.8\ \mu\Omega\,\mathrm{cm}$, the WF law predicts a residual linear term $\kappa_0/T = L_0/\rho_0 = 0.91\ \mathrm{mW\,K^{-2}\,cm^{-1}}$, as drawn in Fig. 2. (Weak localization is not expected to alter the WF law appreciably[5], as verified experimentally in layered graphene[47].)

This complete violation of the WF law shows that the non-superconducting ground state of this copper-oxide material is not a Fermi liquid. The charge carriers responsible for the good electrical conduction do not display the expected fermionic heat transport.

It is instructive to consider the effect of increasing the temperature above zero. Contributions to the heat transport from the electron system (κ_e) and from the ionic lattice (κ_{ph}) will add to give the measured thermal conductivity: $\kappa(T) = \kappa_e(T) + \kappa_{ph}(T)$. These two systems are coupled. It is clear that phonons are scattered by electrons, since the crystal conducts heat better at zero field than at 13 T beyond 0.6 K. In other words, as the temperature is raised, inelastic scattering processes become increasingly effective at limiting the phonon heat flow, and we expect the dominant process to be electron–phonon scattering.

Given this observed electron–phonon coupling, the total phonon scattering in field is the sum of whatever scatters phonons in zero field plus the added scattering that comes from the field-induced electronic excitations. The thermal resistivity of phonons due to electron scattering is given by $W_e^{ph} = BT^{-2}$, where the constant B depends on the strength of the electron–phonon coupling, the electronic density of states, and various other factors[48]. This means that the phonon conductivity at low T is given by $\kappa_{ph} = \kappa(0)[1 + \kappa(0)W_e^{ph}]^{-1}$, where $\kappa(0)$ is the measured zero-field conductivity, assumed to be essentially all phononic. We can put a reasonable lower bound on the electron–phonon coupling parameter B by requiring that the resulting κ_e/T does not decrease with T. Adjusting B such that κ_e/T is constant above 0.3 K gives the curve shown in Fig. 3 for $H = 13$ T (circles). The same can be done for other fields with the resulting values of $\kappa_e/T = 0.6$, 1.2 and $1.9\ \mathrm{mW\,K^{-2}\,cm^{-1}}$ and corresponding values of $B = 0.22$, 0.4, and $0.68\ \mathrm{K^3\,m\,W^{-1}}$ for $H = 2$, 4 and 8 (or 13) T, respectively. (In comparison, electron–phonon coupling in copper gives $B = 4$–$8\ \mathrm{K^3\,m\,W^{-1}}$; ref. 48). We note the self-consistency of this analysis whereby B scales with the value of κ_e/T (above 0.3 K); in other words, by increasing the field from 2 to 4 T—thereby increasing the density of electronic excitations—one increases both the electronic heat conduction and the electron scattering of phonons.

From Fig. 3 we see that $\kappa_e(T)/T$ exceeds the value of L_0/ρ that is appropriate for a Fermi liquid. In other words, the low-energy excitations of the electron system violate the WF law not only at $T \rightarrow 0$, where $\kappa_e(T)/T \ll L_0/\rho_0$, but also at finite temperatures, where $\kappa_e(T)/T > L_0/\rho$ (above 0.2 K). It is important to appreciate that qualitatively the latter violation is independent of our choice of B, in the sense that even if B is set to zero, κ_e/T still exceeds L_0/ρ, in this case by 30% at 0.25 K. We stress that $B = 0$ is unphysical, as it would lead to a negative κ_e/T for $T > 0.6$ K. It is also independent of our assumption that $\kappa(0)$ is entirely phononic; indeed, if some part of $\kappa(0)$ is in fact electronic, then the violation turns out to be even more pronounced. In other words, while there is no accurate way to extract the electronic contribution at 13 T, the fact that the WF law is violated is independent of our model for the phonon conduction and the electron–phonon scattering. The result $\kappa_e(T)/T \approx 2L_0/\rho_0$ above 0.3 K is obtained in several crystals, even though $\rho(T_c)$ varies in the range 20–40 $\mu\Omega\,\mathrm{cm}$.

We have investigated the possibility that our measurement gradually ceases to detect the electronic heat current as electrons fall out of thermal equilibrium with the phonon bath when the temperature approaches $T = 0$ K. We can imagine this happening when the electrical contact resistance between the heater and the sample is too large and the heat is predominantly carried by the phonons. This might then explain the drop in κ_e/T measured below 0.3 K or so (see Fig. 3). Two facts lead us to rule out electron–phonon decoupling as the main mechanism for the drop. First, identical data is obtained by sending heat directly through the electron system using photons[49]. Secondly, a similar drop is observed in samples of optimally doped $(La, Sr)_2CuO_4$, where we have achieved electrical contact resistances that are 100 times lower than in our PCCO samples, namely $\sim 10\ \mathrm{m\Omega}$. We therefore believe this low-temperature drop is intrinsic and not specific to PCCO.

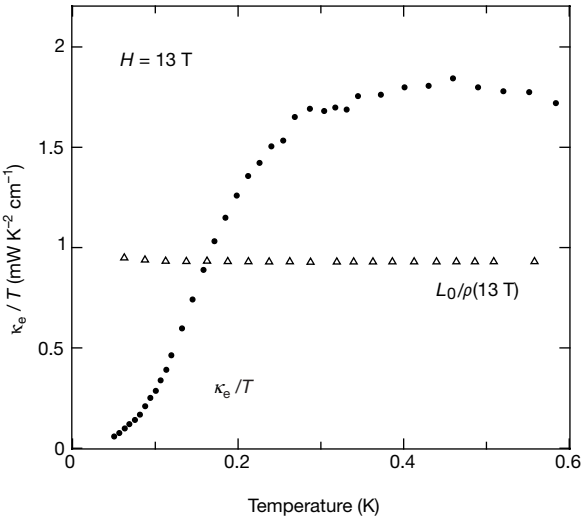

Figure 3 Comparison of charge conductivity $\sigma(T) = 1/\rho(T)$, plotted as $L_0/\rho(T)$ (triangles), and electronic heat conductivity κ_e, plotted as κ_e/T (circles), as a function of temperature in the normal state at $H = 13$ T. The electronic contribution to the heat conduction is the difference between the measured κ(13 T) and the phonon contribution κ_{ph}(13 T), estimated in the text. In a Fermi liquid, the curve of κ_e/T would lie precisely on the data for L_0/ρ_0. Below $T = 0.15$ K, $\kappa_e \approx T^{3.6}$.

Discussion

The copper oxide PCCO is the first material, to our knowledge, to violate the Wiedemann–Franz law. The breakdown of this robust signature of Fermi-liquid theory suggests that the fundamental entities that carry heat, charge (and spin) in the copper oxides are not the usual Landau quasiparticles. The fact that the electron system conducts heat in a way that is largely unrelated to the way it carries charge at low temperature points to the existence of neutral excitations responsible for much of κ_e. If these neutral excitations are fermions, that is, spinons, they should contribute a constant term to κ_e/T, as may well be the case for $T > 0.3$ K. The drop seen at the very lowest temperatures then remains to be explained, and the possibility of spinon localization should be considered.

This study is limited to a single carrier concentration, near optimal doping, in the whole phase diagram. It will be interesting to investigate the evolution with doping of this emerging picture. If the WF law is satisfied in overdoped copper oxides, where Fermi-liquid theory is generally assumed to hold, our results on optimally doped PCCO suggest that a violation of the law is a property of underdoped copper oxides. A comprehensive study will shed light on the gradual breakdown of Fermi-liquid theory in the copper oxides as the carrier concentration is reduced towards the Mott insulating state. □

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