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# Phenomenological description of the copper oxides as almost localized Fermi liquids

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We demonstrate that a variety of normal-state properties of the cuprates are similar to what is observed in heavy-fermion metals, provided that the temperature or frequency are rescaled. This leads to a characteristic energy scale $T_{coh} \simeq 150$ K and suggests that the "non-Fermi-liquid-like" behavior of the cuprates is related to the high-temperature breakup of coherence of a Fermi-liquid ground state. We propose a concrete physical picture for future theories and give predictions which can be tested.

There is a growing concensus that the normal state of the high-temperature superconductors is close to, but nevertheless different from, a canonical Fermi liquid. A number of alternative pictures[1] have been proposed for this state which assume that the metallic phase is distinctly different from all metals which have been previously encountered. Here we build on the observation that the heavy-fermion metals are reasonably well-documented examples of a Fermi-liquid state (for $T < T_{coh} \sim$ several kelvin) which is slowly disintegrating with increasing temperature, until at temperatures $T_{loc}$ of the order of 50–100 K the $f$ electrons behave as independent local moments. By comparing various properties, we show how the heavy fermions can be used as a kind of "road map" for interpreting anomalous behavior and thereby provide a possible prototype for the cuprates.

In the region of partial coherence the properties of the heavy-fermion metals show distinct deviations from Fermi-liquid behavior: the resistivity does not vary as $T^2$, the NMR relaxation exhibits deviations from Korringa behavior, and the Hall coefficient displays an unusual temperature dependence which is characteristic of neither the low-temperature (roughly $T$ independent) nor high-temperature skew scattering regime. In some heavy-fermion materials, such as $UBe_{13}$, superconductivity intervenes before full coherence is established. The heavy fermions may be viewed as being on the verge of a localization transition, in some ways similar to the metal-insulator transition of the cuprates. If, for example, Pt is replaced by Pd in $UPt_3$ the $f$ electrons originating on the U sites become localized.[2]

By exploring the analogy with the heavy fermions, we argue that in the cuprates the "anomalous" normal-state behavior is to be associated with the partial coherence of the $d$ electrons. They are neither fully itinerant nor are they localized as in a "two component" picture. In this scenario the controversy arising from the localized versus itinerant descriptions, which has plagued the field, can be analyzed. It has been inferred from a variety of experiments that the Cu moment is nearly full and the valence state is close to +2. On the other hand, there is clear evidence from some of these same measurements that hybridization between the Cu and O states does occur in the metallic phase. This suggests a picture in which the $3d$ electrons are almost localized.

On the basis of the analogy between the Hamiltonians, we and others[3,4] have studied various properties of the metallic copper oxides within the same Fermi-liquid formalism which has been applied to describe the coherent state of the heavy fermions. This approach has been reasonably successful in addressing both transport and magnetic data in the metallic regime. In recent NMR calculations[4] we found that at optimal stoichiometries the characteristic temperature scale $T_{coh}$ ranges from about 100 to 200 K. This would correspond to an effective mass roughly 100 times smaller than that of the heaviest heavy fermion $CeCu_6$, where $T_{coh}$ is around 1 K. With increasing hole concentration $T_{coh}$ increases. The insulator corresponds to a Mott localization transition in which the effective mass gets arbitrarily large, i.e., $T_{coh}$ becomes small. At high doping concentration there should be a regime in which $T_c/T_{coh}$ is sufficiently small compared to 1.0 so that the normal state exhibits the canonical Fermi-liquid properties. On the other hand at optimal stoichiometries $T_c/T_{coh}$ is close to unity so that a description based on a fully coherent Fermi liquid is only a first approximation.

On the basis of the above microscopic picture and in order to analyze a variety of different experiments in the cuprates and heavy fermions, we introduce a rescaled heavy-fermion temperature and frequency parameter $T^* = 100\ \mathrm{T}\ (\gamma/\gamma^{CeCu_6})$, with a similar definition for $\omega^*$. Here $\gamma$, which is proportional to the effective mass, is the linear temperature coefficient in the electronic specific heat which is well known for the heavy fermions. In this way we can replot data in various heavy-fermion metals on a universal scale compatible with that of the copper oxides. We now explore the consequences of this analogy.

## NMR RELAXATION

In Fig. 1(a) the measured[5] nuclear relaxation rate $1/T_1$ at the Cu site for $La_{1.85}Sr_{0.15}CuO_4$ is plotted as a function of $T$. Figure 1(b) plots[6] this same quantity for $CeCu_6$. In all our plots of heavy fermion data the abscissa corresponds to the rescaled temperature $T^*$ (or frequency $\omega^*$). The vertical axis has not been rescaled. We know of no heavy-fermion NMR data on the $f$ electron site which

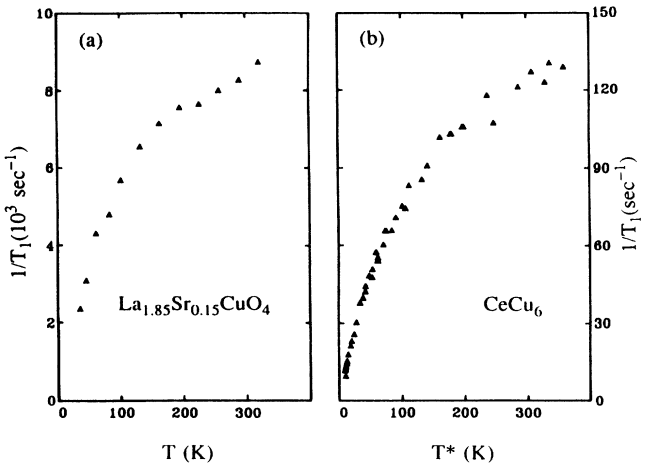


FIG. 1. The temperature dependence of the Cu nuclear spin-lattice relaxation rates for (a) $La_{1.85}Sr_{0.15}CuO_4$ and (b) $CeCu_6$. The rescaled heavy-fermion temperature $T^*$ is defined in the text.

would be the natural counterpart for the Cu site in the oxides. It may be presumed that via intersite transfer hyperfine coupling, the characteristic $1/T_1$ measured in the Cu resonance of $CeCu_6$ follows that of the $f$ site, since the characteristic $T$ dependences are consistent with those deduced from other data. In may be seen that for both the copper oxides and heavy-fermion systems, at low temperatures the relaxation follows the Korringa law from which deviations become apparent around $T_{coh}$, just as is seen for the copper oxides. (Because there are only a few points in the low-temperature regime of the oxides, we rely here on the observation[5] that Cu and O NMR relaxations exhibit the same $T$ dependence at low $T$ and that the latter is found to be Korringa-like.) The heavy-fermion measurements can be followed to considerably higher temperatures where the relaxation rate saturates to a $T$-independent value. The behavior shown in Figs. 1(a) and 1(b) is consistent with that observed in other copper oxides as well[6] as in $UPt_3$, $CeCu_2Si_2$, and $UBe_{13}$ when the rescaled temperature $T^*$ is used.

## ac CONDUCTIVITY

The frequency dependence of the ac conductivity[7] $\sigma(\omega)$ in $YBa_2Cu_3O_{7-\delta}$ (with $T_c=80$ K) is replotted in Fig. 2(a). Figure 2(b) shows the analogous data[8] on $UPt_3$ in terms of the rescaled $\omega^*$. In both systems there is a low $\omega$ Drude contribution whose $T$ dependence is related to the dc conductivity followed by an additional absorption feature and a broad continuum. The same qualitative behavior is seen in all the metallic copper oxides (as well as[9] BaKBiO and BaPbBiO). The data in other heavy-fermion systems is similar.[8] At room temperature, the entire structure plotted here for $UPt_3$ has disappeared[8] suggesting that all the features shown appear to be consequences of the coherent or "transition" regimes.

## TEMPERATURE DEPENDENCE OF THE HALL COEFFICIENT

The Hall coefficient is plotted[10] as a function of temperature for $La_{1.8}Sr_{0.2}CuO_4$ in Fig. 3(a). The same general $T$ dependence is seen in all the epitaxial LaSrCuO films of Ref. 10 for Sr concentrations in excess of 0.1. Similar temperature dependences (above the maximum) are seen in the $YBa_2Cu_3O_{7-\delta}$ family, as well as in Bi and Tl compounds.[10] The maximum at $T\sim100$ K has also been reported in other systems.[11] For comparison, we have selected the heavy fermion $UBe_{13}$ [Fig. 3(b)] which may be like the optimally doped cuprates in that it never exhibits fully coherent behavior.[12] Also indicated in Figs. 3(a) and 3(b) is the inverse of $eR_H$, called $n_H$, which in a Fermi-liquid picture should *not* be identified with the carrier number. The very small magnitude of $n_H$ in $UBe_{13}$ serves to emphasize this point. In the higher temperature regime, the effects of skew scattering ($R_H\sim\chi\rho$) are known to be important in the heavy-fermion materials but both $\chi$ and $\rho$ show a much weaker $T$ dependence than $R_H$ for the $T^*$ shown here.[12] While we have selected $UBe_{13}$ as an example, the general shape of $R_H$ with a high maximum followed by a slow decrease is also seen in $CeCu_6$,

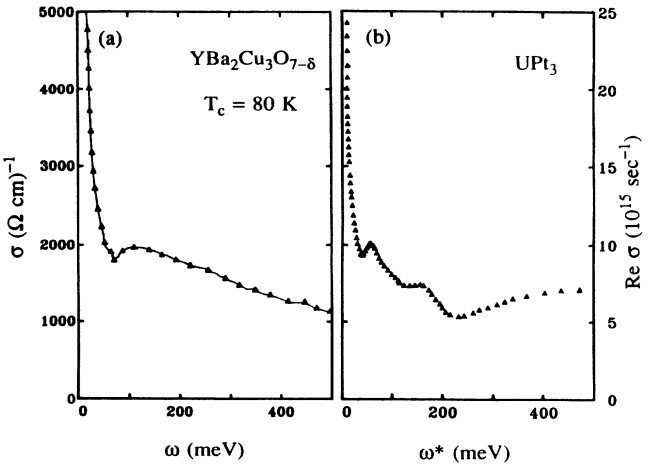


FIG. 2. The frequency dependence of ac conductivity for (a) $YBa_2Cu_3O_{7-\delta}$ ($T_c=80$ K) and (b) $UPt_3$.

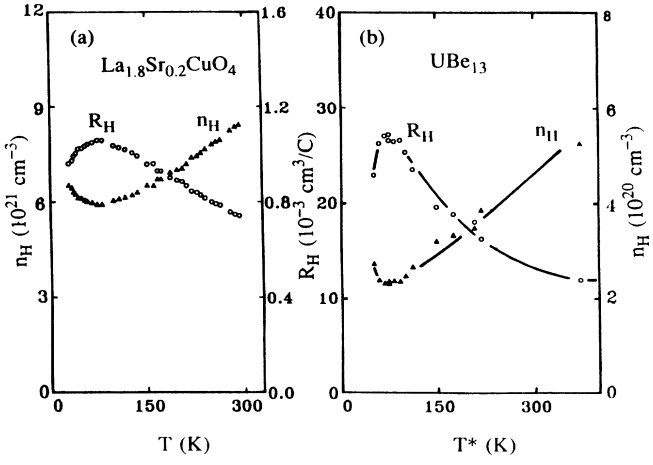


FIG. 3. The temperature dependence of the Hall coefficient $R_H$ and its inverse $n_H=1/eR_H$ for (a) $La_{1.8}Sr_{0.2}CuO_4$ and (b) $UBe_{13}$.

$UPt_3$, $UAl_2$, etc., for temperatures above the coherence temperature (but still lower than the skew scattering regime).

## TEMPERATURE DEPENDENCE OF THE THERMOPOWER

In the heavy fermions the thermopower $S(T)$ has a nonuniversal temperature dependence. Nevertheless, it is generally believed that structure in $S(T)$ reflects the characteristic transition to the coherent regime. We emphasize the need in the cuprates for determining the intrinsic characteristic form for $S(T)$ which might, like $R_H$, be expected to be fairly universal. In Fig. 4(a) the temperature dependence of the thermopower is plotted for two different cuprates[13] which are fairly representative of the types of behavior seen. The same broad maximum seen in $La_{1.8}Sr_{0.2}CuO_4$ has also been seen in the Ba substituted system, BiSrCaCuO, and in Tl based oxides,[13] all at temperatures between roughly 100 and 200 K. Measurements on $YBa_2Cu_3O_7$ are also similar, although, this broad maximum is not always as apparent. Single-crystal data on this $YBa_2Cu_3O_{7-\delta}$ system indicate the presence of a minimum as well as a maximum, as shown in Fig. 4(a). The analogous measurements for two different heavy-fermion metals are shown[14] in Fig. 4(b). Here the characteristic temperature dependences are similar, but the extrema occur at temperatures somewhat different from $T_{coh}$. In the copper oxides, phonon drag effects above the high transition temperatures may make the behavior of $S(T)$ more complex. The moderately heavy fermion $UAl_2$ has a behavior similar to $UPt_3$ but with a negative sign so that there is a minimum in $S$, slightly above $T_{coh}$. By contrast $CeCu_6$ has a shoulder[14] rather than an extremum near $T_{coh}$.

## TEMPERATURE DEPENDENCE OF THE MAGNETIC SUSCEPTIBILITY

The magnetic susceptibility of many of the cuprates exhibits some deviations from a Pauli (constant in $T$) behavior. The exceptions are in fully oxygenated $YBa_2Cu_3O_7$ and Tl- and Bi-based cuprates. In the heavy-fermion metals, similar deviations from a strict Pauli behavior are also seen to a greater or lesser degree. We illustrate these points in Fig. 5. Three characteristic temperature dependences are found in both copper oxides[15] and heavy fermions:[16] either $\chi$ monotonically decreases, or it has a slight maximum at intermediate temperatures followed by a saturation and sometimes a decline as $T$ increases. The extreme limit of these various categories is a nearly constant susceptibility. In the susceptibility of the heavy fermions this same variety of behavior is shown in Fig. 5(b). (For $CeAl_3$, the plot reflects low-temperature data measured in Ref. 16.) It should be noted that in the heavy fermions, where the high-temperature regime can be fully accessed, there is a gradual decrease in $\chi$ until finally the $1/T$ Curie-Weiss asymptotic behavior is reached at $T_{loc}$. The corresponding energy for the copper oxides is 10000 K so that these metals will never exhibit the local-moment phase for any accessible laboratory temperatures. In the cuprates, when $\chi$ is found to exhibit a high-temperature falloff, it has sometimes been attributed to impurity contaminations which are often subtracted out. It should be stressed that there are considerable sample variations and sensitivities seen in $\chi$ in both the heavy-fermion and copper oxide metals. For this reason, this parameter is not ideally suited for determining the size of $\gamma$ or the coherence energy scale in the copper oxides.

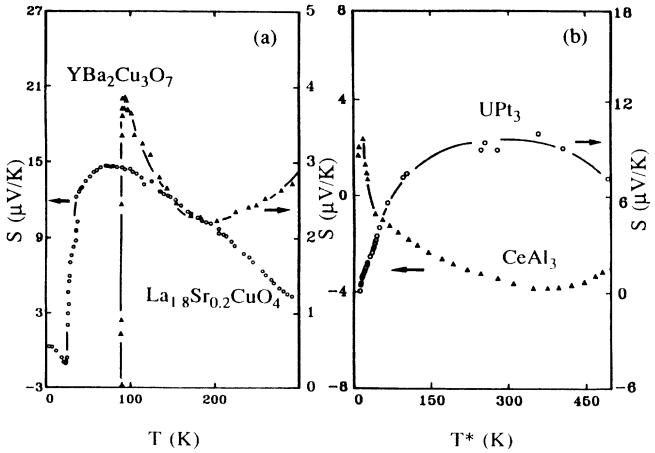


FIG. 4. The temperature dependence of thermopower for (a) $La_{1.8}Sr_{0.2}CuO_4$ and $YBa_2Cu_3O_7$; (b) $CeAl_3$ and $UPt_3$.

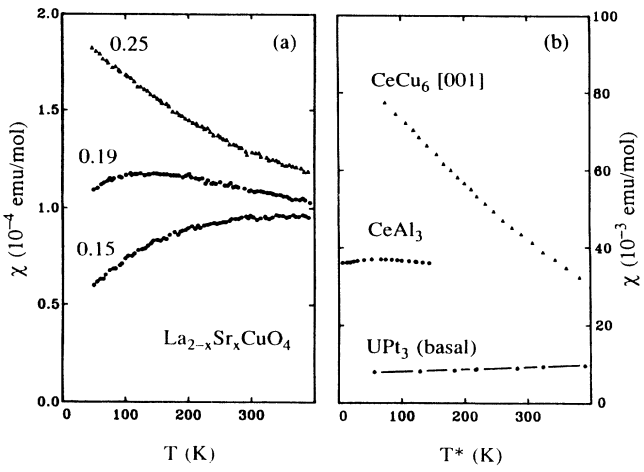


FIG. 5. The temperature dependence of the static uniform magnetic susceptibility for (a) various doping concentrations of La cuprates and (b) various heavy fermions.

## RESISTIVITY, THERMAL CONDUCTIVITY, RAMAN SCATTERING, AND NEUTRON CROSS SECTION

Above $T_c$ electron-electron scattering dominates the resistivity of the heavy fermions, although it assumes the canonical $T^2$ dependence only for temperatures $T_\rho$ considerably smaller than $T_{coh}$. (In $CeCu_6$, $T_\rho$ is $\sim 0.1$ K whereas in $UPt_3$ it is closer to 2 K.) From $T_\rho$ to roughly $3T_\rho$ the heavy fermions exhibit[12,17] a *linear* contribution to the resistivity arising from electron-electron scattering.

In $UBe_{13}$ and some samples of $CeCu_2Si_2$ this appears at, and persists above, $T_c$.[12,17] In the copper oxides at $T_c$, electron-phonon scattering has an unavoidable contribution to $\rho$ which prevents us from performing a simple rescaling of the heavy-fermion data. However, following the same reasoning presented above, there should also be a "residue" of the higher-temperature electronic contribution which is linear in temperature as seen in the heavy fermions. Phonons may also play a role in the thermal conductivity and thermopower. In the former, it has been estimated[13] that they account for roughly 90% of the measured value, despite the fact that the temperature dependence is consistent with the Wiedermann-Franz law.

Much attention has been paid to the electronic Raman continuum in the cuprates. In similar experiments on the heavy fermions there are no clear indications of the onset of coherence. There is therefore no basis for a comparison of Raman data (within the coherent regime) between the two classes of systems at this time. As for neutron-scattering experiments, while precise analogies cannot be made yet, it is clear in both classes that the characteristic frequency and related temperature $T_{coh}$ are evident in the data.

In summary, we have argued by the heavy-fermion example that the anomalous normal-state properties of the cuprates are consistent with a *partially coherent* Fermi liquid. In this transition regime, for $1/T_1$, $R_H$, and $\sigma(\omega)$, the behavior in both systems appears to be rather universal. At optimal stoichiometries this "marginality" may not be easily distinguished from that advocated by others.[1] However, overdoped systems for which $T_c/T_{coh}$ is made sufficiently low are predicted to provide a "window" on the coherent Fermi-liquid state. By contrast as the insulator is approached, with decreasing $T_{coh}$, more incipient "local"-moment behavior is expected, which is associated with large and temperature-dependent $R_H$, non-Korringa NMR behavior, etc. Our work also yields a basis for addressing inter-relationships between the data upon which future experiments can focus, i.e., characteristic energy scales. Finally, it provides a physical picture which should aid in constructing theories of the superconducting transition, which seems to occur in surprisingly close proximity to the onset of coherence in both the heavy-fermion and high-$T_c$ superconductors.

## ACKNOWLEDGMENTS

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