A Short Review of Non Fermi Liquids

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Abstract

The low temperature properties of ordinary metals became well known with Landau's development of Fermi liquid theory in the late 1950s. In some heavy fermion compounds, the predictions of this theory have been extremely accurate. In recent years, however, a new class of heavy fermion materials has become the subject of increased scrutiny because they possess unusual thermodynamic and magnetic properties that cannot be explained by conventional Fermi liquid theory. These materials are known as non Fermi liquids. Although the mechanism that drives the difference in the behaviour of these seemingly similar heavy fermion systems is not fully understood, the low temperature physical properties of non Fermi liquids can be characterized and compared to those of conventional Fermi liquids. This paper attempts to classify the differences in these materials as well as provide some general information about non Fermi liquids.

1 Fermi Liquids

In order to better understand the low temperature properties of non Fermi liquids (NFL), it is useful to grasp the essential nature of some heavy fermion systems that behave like "ordinary" Fermi liquids. Fermi liquid theory (FLT), originally introduced by Landau in 1956, has formed the basis of our understanding of metallic systems. The basic premise of this theory is that a one-to-one correspondence exists between the excitations of a free Fermi gas and the interacting conduction electrons in a metallic system. [2] [4] Another underlying idea in this theory is the existence of a single energy scale. This suggests that if the temperature and energy dependence of experimentally measured quantities, such as the specific heat, resistivity and magnetic susceptibility, are consistent with the intrinsic energy scale of the electronic excitations, i.e. the Fermi energy, then the material behaves like a Fermi liquid. [5]

So what are the physical properties of a heavy fermion system that is described by FLT? Qualitatively, one expects that the electrical resistivity should increase with increasing temperature, as is the case for ordinary metals like copper. It turns out that this is not the case for heavy Fermi liquids. To illustrate this behavior, consider $CeAl_3$. $CeAl_3$ provides an excellent example for illustrating the physical characteristics of these heavy fermion systems, as it was one of the first discovered heavy electron compounds. Figure 1 shows the resistivity of $CeAl_3$ for both high and low (inset) temperatures.

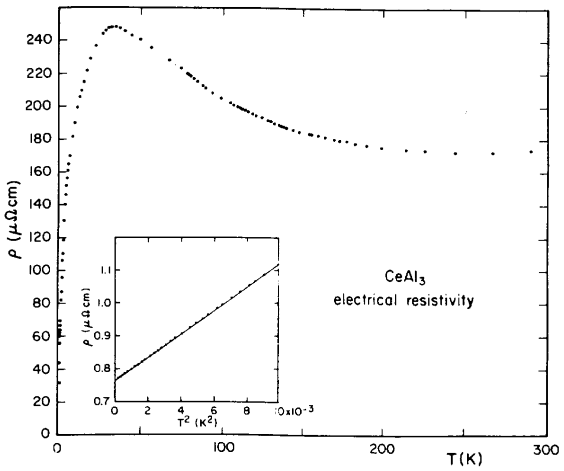

Figure 1: *ρ(T) of $CeAl_3$ between 1.5 and 300 K and below 0.1 K. Data are from Ott et al. (high temperature) and Andres et al. (low temperature). Taken from [3].*

Contrary to ordinary metals, ρ(T) has a minimum just below room temperature (300 K) and increases with decreasing temperature, until about 35 K. At this temperature, the resistivity reaches a maximum. As the temperature continues to decrease, ρ(T) correspondingly decreases. For extremely low temperatures, ρ(T) can be well approximated by

$$\rho(\mathrm{T}) = \rho_0 + \mathrm{A}\, T^2$$

where ρ_0 is the resistivity at zero temperature and A is a constant, both of which vary for different materials. This model fits the data well up to roughly 0.3 K. [3]

In heavy fermion materials, the low temperature specific heat also behaves unlike ordinary metals, for which it has a finite value at zero temperature and slightly increases linearly with increasing temperature. Figure 2 illustrates the contrasting low T behaviour of the specific heat for $CeAl_3$.

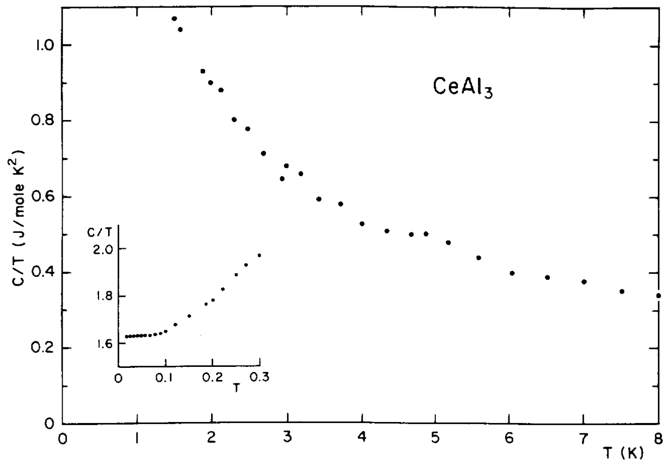

Figure 2: *Low temperature specific heat C/T versus T for $CeAl_3$. The data for $T > 1.5$ K are from Ott et al., those below 0.3 K from Andres et al. Taken from [3].*

Here, the specific heat increases with *decreasing* temperature. It reaches a maximum somewhere between 0.3 and 1 K. After the maximum, the specific heat decreases and obtains a finite value at zero temperature which is much larger than that of ordinary metals (2000 times greater than copper, for example). This is a result of the large effective mass of these "heavy" fermion materials. [3]

2 Non Fermi Liquids

Now that the properties of a Fermi liquid have been described, the problem of classifying non Fermi liquids begins. Several different materials exhibit NFL behaviour; most are cerium and uranium intermetallics that have been doped with a nonmagnetic material. The Ce and U ions have partially filled f-electron orbitals that interact with the conduction electrons in the materials, most certainly contributing to the NFL behaviour observed in these intermetallics. Some examples of NFLs are $U_{1-x}Th_xPd_2Al_3$, $M_{1-x}U_xPd_3$ (M=Sc, Y), and $UCu_{5-x}Pd_x$. These materials differ from Fermi liquids in that they exhibit either logarithmic or weak power law divergences in some physical characteristics, including the electrical resistivity and specific heat, at low temperatures.[1] In fact, it seems that NFLs are defined more by their low temperature behaviour than from an all-encompassing definition as was the case for Fermi liquids. Recall that Fermi liquids were defined as materials displaying universal behaviour for energies less than the Fermi energy. Analysis NFLs indicates that the scaling of electronic excitations in NFLs are more varied than predicted for Fermi liquids. In fact, this variable energy scale is believed to contribute to the NFL behaviour, and is also included in the working definition of NFLs. [5]

As previously mentioned, deviation from Fermi liquid has recently been observed in several f-electron intermetallics, including $Y_{0.8}Th_{2-x}U_xPd_3$. In contrast to the quadratic temperature dependence of the resistivity of Fermi liquids at low temperatures, the low temperature resistivity for non Fermi liquids is given by

$$\rho(\mathrm{T}) \sim \rho_0 \text{ - A T}$$

where ρ_0 indicates the resistivity at zero temperature and A is a constant. As in the case for Fermi liquids, these constants are material dependent, and are related to the relevant energy scale for the material. Figure 3 illustrates the low temperature behaviour of the resistivity of $Y_{0.8}Th_{2-x}U_xPd_3$.

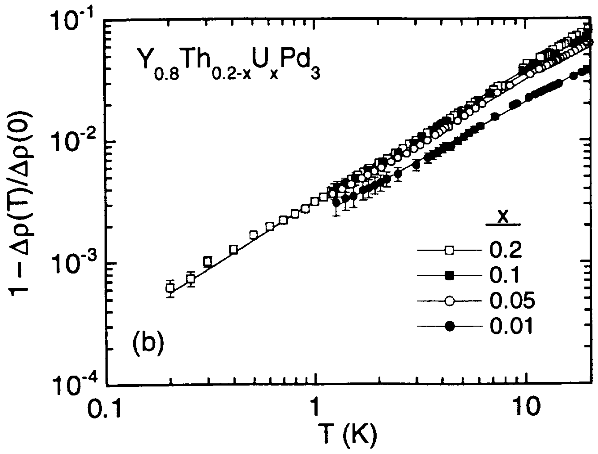

Figure 3: *Low temperature resistivity data (T $\leq$ 20 K) plotted as log(1 - $\Delta\rho(T)/\Delta\rho(0)$) versus log T for the alloy* $Y_{0.8}Th_{2-x}U_xPd_3$ ($0 \leq x \leq 0.2$). *Solid lines represent fits to a power law* $\Delta\rho(T)/\Delta\rho(0) = 1 - a(T/T_k)^n$ *(n $\approx$ 1 $\pm$ 0.2), revealing non Fermi liquid behaviour. Taken from [1].*

Note that in this plot, the vertical axis has a different functional form than the resistivity plotted for $CeAl_3$. This does not mean that the two plots are not related; figure 3 simply illustrates the normalized resistivity for $Y_{0.8}Th_{2-x}U_xPd_3$. Also note that the resistivity has been fitted to T^n. In constrast to Fermi liquids where n is typically 2 (quadratic), the value of n for for the example show here is approximately 1.0 $\pm$ 0.2 (a similar result holds for other NFLs). This result is also in agreement with the predicted linear temperature dependence of the resistivity.

The specific heat of non Fermi liquids also differs from that of a Fermi liquid. It is given functionally by

3 Conclusions

So why are NFL materials important? As indicated above, a great deal of the interest in NFL behaviour simply results from the unusual temperature dependence of the physical characteristics of NFLs. NFL materials have also become increasingly more important as they display unconventional superconductivity that has also been observed in some copper oxides. While these oxides differ from heavy fermion systems, they have strikingly similar superconducting states (aside from the different observed critical temperatures.) It is hoped that an understanding of the NFL systems will not only aid in the understanding of the nature of the elecronic excitations in these f-electron materials, but also in the understanding of this unconventional superconductivity. [1]

The mechanism that drives the difference between Fermi liquids and NFLs is not fully understood, but many theories exist. Most agree that the behaviour of NFLs is the result of several interactions. One idea is that many of the observed properties may be understood as a consequence of a broad distribution of Kondo temperatures, although this is probably only part of the explanation.

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