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Non-Fermi liquid behavior as a consequence of Kondo disorder

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Abstract

We describe a route based on disorder towards non-Fermi liquid behavior in Kondo alloys. Disorder in the f-parameters leads to a distribution of local Kondo temperatures, $P(T_K)$. When this distribution is such that $P(0) \neq 0$, the system exhibits non-Fermi liquid behavior, due to the presence of dilute low-T_K spins which are unquenched at finite temperatures.

Keyword: Non-Fermi liquid system

There are by now several f-electron metals which show non-Fermi liquid (NFL) behavior [1]. Typically, they show $C_V(T)/T \sim \ln(\Gamma/T)$, $\chi(T) \sim \ln(\Gamma/T)$ or $T^{-\alpha}$ and $\rho(T) \sim \rho_0(1 - T/T_0)$. The origin of the NFL behavior in these alloys remains controversial.

In this article, we will show a route towards NFL behavior which relies on the disordered nature of these alloys [2]. We were motivated by the Cu NMR study of Ref. [3], which showed that the broad NMR lines in $UCu_{5-x}Pd_x$ ($x = 1$ and $x = 1.5$) could only be explained by the presence of microscopic disorder of a short-range nature. A simple disorder model was then used to describe both the thermodynamics and the NMR line widths.

Our point of departure is a disordered Anderson lattice Hamiltonian

$$H = \sum_{ij\sigma} -t_{ij}\left(c^\dagger_{i\sigma}c_{j\sigma} + \text{h.c.}\right) + \sum_{j\sigma} E^f_j f^\dagger_{j\sigma} f_{j\sigma} + \sum_{j\sigma}(V_j c^\dagger_{j\sigma} f_{j\sigma} + \text{h.c.}) + U\sum_j n_{fj\uparrow} n_{fj\downarrow}. \quad (1)$$

We will take $U \to \infty$ in the remainder of the paper. We assume the parameters E^f_j and V_j are distributed according to some general distribution functions $P_1(E^f)$ and $P_2(V)$, respectively, which are *not* assumed to be very broad.

We will focus on the dynamical mean field theory of correlations and disorder [4], which becomes exact in the limit of large coordination. The problem is then reduced to the solution of an *ensemble* of impurity problems in a self-consistently determined conduction electron bath $\Delta(\omega)$, which is defined by the following effective action and self-consistency condition (for a semi-circular density of states):

$$S^{\text{imp}}_j = T\sum_{\omega_n\sigma}\left[f^\dagger_{j\sigma}\left(-i\omega_n + E^f_j + V^2_j\Delta(i\omega_n)\right)f_{j\sigma}\right], \quad (2)$$

$$\Delta(\omega) = \frac{1}{\omega + \mu - t^2\overline{G}_c(\omega)}, \quad (3)$$

$$\overline{G}_c(\omega) = \left\langle \frac{1}{\omega + \mu - t^2\overline{G}_c(\omega) - \frac{V^2_j}{\omega - E^f_j - \Sigma^f_j(\omega)}} \right\rangle^{\text{av}}, \quad (4)$$

where μ is the chemical potential, t is the hopping amplitude, $\overline{G}_c(\omega)$ is the self-averaged conduction electron Green's function, $\langle\cdots\rangle^{\text{av}}$ denotes the disorder average and $\Sigma^f_j(\omega)$ is the f-self-energy under the action (2). Details of the equations will be given elsewhere [2].

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Each impurity problem (2) is governed by the Kondo temperature scale given, in the Kondo limit, by

$$T_{Kj} = De^{-1/\lambda_j} \qquad (\lambda_j \equiv 2\rho_0 V_j^2/|E_j^f|), \tag{5}$$

where $\rho_0 = \mathrm{Im}\,\Delta(0)$. The distributions of f-parameters $P_1(E^f)$ and $P_2(V)$ will give rise to a distribution of Kondo temperatures $P(T_K)$. It can be shown that [2], to a high degree of accuracy, the thermodynamic response of the disordered lattice will be given by an average over the single-impurity results with $P(T_K)$. Due to the strong exponential dependence in Eq. (5), a moderately broad distribution of λ_j's will give rise to a *rather broader* distribution $P(T_K)$. Fig. 1 depicts the $P(T_K)$ appropriate for $UCu_{5-x}Pd_x$ according to Ref. [3]. Note that $P(0) \neq 0$ for both distributions. This has profound effects on the behavior of the system.

Let us consider for example the susceptibility χ. For a single impurity, it obeys a scaling form $T_K\chi(T) \propto f(T/T_K)$, where [5]

$$f(x) \approx \begin{cases} \alpha - \beta x^2 & x \ll 1; \\ \frac{\gamma}{x}\left(1 - \frac{1}{\ln x}\right) & x \gg 1, \end{cases} \tag{6}$$

α, β and γ being universal numbers. Since $P(0) \neq 0$, one can expand $P(T_K) = P_0 + P_1 T_K + \cdots$ for T_K up to an arbitrary cutoff Γ. Thus, taking the average

$$\langle \chi(T) \rangle^{av} \propto \int_0^\infty \frac{dT_K}{T_K} P(T_K) f\left(\frac{T}{T_K}\right)$$
$$\approx \int_0^{\Gamma/T} \frac{dy}{y} P_0 f(1/y) \sim \alpha P_0 \ln\left(\frac{\Gamma}{T}\right), \tag{7}$$

since the integral is dominated by its upper limit. This log-divergent NFL susceptibility (and similarly for $C_V(T)/T$) is observed in $UCu_{5-x}Pd_x$. As seen in Fig. 1, at a temperature T, there are always a few f-sites with $T_K \ll T$. While the remainder of sites have undergone quenching and effectively fallen out of the problem, these low-T_K spins remain unquenched and dominate the low temperature behavior. The response is dominated by rare events at the tail of the distribution function, rather than by the average spin, a situation commonly called a Griffiths phase [6]. If $P(0) = 0$, all spins freeze out at some finite temperature and Fermi liquid behavior is recovered.

Whereas thermodynamic quantities are given by the average over single-impurity results, transport properties are more subtle. Indeed, the well-known onset of coherence at low temperatures, typical of clean

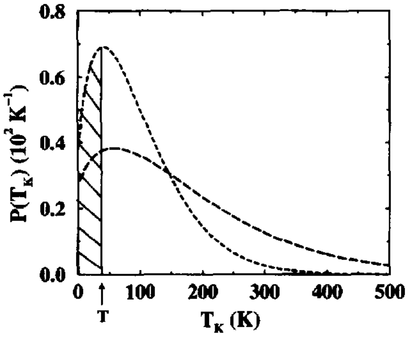

Fig. 1. Experimentally determined $P(T_K)$ for $UCu_{5-x}Pd_x$: $x = 1$ (long-dashed line), $x = 1.5$ (dashed line) (from Ref. [3]). The shaded area below T represents the low-T_K spins which remain unquenched at temperature T.

heavy fermion materials bears no resemblance to the incoherent single-impurity resistivity. However, the dynamical mean field theory is able to account for coherence in a natural way, while at the same time exhibiting incoherent scattering at intermediate and high temperatures [7]. Besides, sufficient disorder is able to completely destroy coherence in the low temperature transport [2]. Indeed, by using the slave boson mean field theory to solve the *ensemble* of impurity problems at $T = 0$, we have shown that the strong f-site correlations lead to an *enhancement* of the effective disorder experienced by the conduction electrons [2].

Once the disorder strength is large enough, all trace of coherence is destroyed. The resistivity is then a monotonically decreasing function of temperature, much like the behavior of a system of dilute Kondo impurities. But the temperature dependence can be non-trivial, especially at low temperatures. To see that, let us analyze the conduction electron self-energy in the dynamical mean field theory. It can be shown that [2]

$$\Sigma_c(\omega) = \frac{\langle T_j^{imp}(\omega) \rangle^{av}}{\overline{G}_c(\omega)(\omega + \mu - t^2\overline{G}_c(\omega))}, \tag{8}$$

where $T_j^{imp}(\omega)$ is the T-matrix of site j. At low temperatures, the temperature dependence of $\Sigma_c(\omega)$ will determine the DC conductivity through the Kubo formula (within this approach there are no vertex corrections).

The temperature dependence of $\Sigma_c(\omega)$ strongly depends on the structure of $P(T_K)$ at low T_K's. Fig. 2 shows the imaginary part of the T-matrix averaged

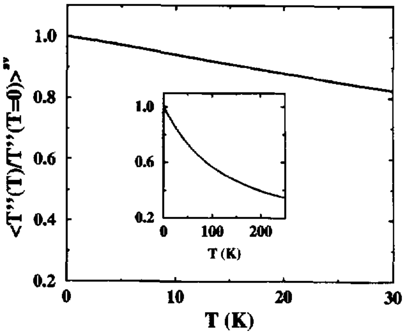

Fig. 2. Imaginary part of the single impurity T-matrix averaged with the $P(T_K)$ for $UCu_{3.5}Pd_{1.5}$, from Ref. [3]. The inset shows the same quantity over a wider temperature range.

over disorder. The leading temperature dependence is linear and leads to a resistivity $\rho(T) \approx \rho_0 - AT$, as observed in $UCu_{5-x}Pd_x$ [8]. The condition for NFL behavior is again $P(0) \neq 0$. As long as $P(0) \neq 0$, the linear behavior of Fig. 2 is observed. If $P(0) = 0$ or negligible, Fermi liquid behavior is recovered. Again, the anomalous NFL behavior is due to the gradual unquenching of low-T_K spins. At a temperature T, spins with $T_K \ll T$ enter their high temperature perturbative regime and effectively cease to contribute to the overall scattering. Since they form a *dilute* system of excitations at low T, their effect is additive and an average over their subtracted contribution can be performed.

In conclusion, we have presented a route to NFL behavior driven by Kondo disorder, whereby a dilute system of low-T_K spins dominates the low temperature response and leads to the anomalous behavior.

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