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Study of the instability of the single-impurity multichannel ground state to inter-impurity interactions

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Abstract

We study a two-impurity, two-channel Kondo model, focusing on the behavior near the limit of two independent impurities. We find that significant departures from the independent regime develop below a crossover temperature which scales approximately as the tenth power of a parity asymmetry.

The one-impurity, two-channel Kondo model has been the object of much renewed interest recently [1]. The importance of this model is the stable non-Fermi liquid ground state that occurs when the coupling constants of the two channels are equal. One way to investigate the robustness of the ground state is to study the effects of adding a second impurity some finite distance from the first. Numerical renormalization group results [2] indicate that the additional interactions induced by a second impurity destabilize the single-impurity point in all phase-space directions. In this paper we study the region in phase space around the single-impurity point where destabilization is taking place. In particular we will discuss two aspects: scaling along the vertical ($J_e - J_o$) axis (all terms to be defined below) and the shape of the boundary between the marginal and Kondo ground state behavior.

The model we study is of two spin-1/2 impurities interacting directly with two channels of conduction electrons, and indirectly, via RKKY interactions, with each other. The Hamiltonian is

$$H = \sum_c \int d^3k\, \varepsilon_{k\mu} c^\dagger_{kc\mu} c_{kc\mu} - J \sum_{c,i} s_c(r_i) \cdot S_i \qquad (1)$$

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where c is the channel index, μ the spin, and i the impurity number (each of the indices c, μ and i take on only two possible values here). Having introduced a second impurity to the single-impurity ($i \equiv 0$) version of this model, we have added two additional interactions: (a) the RKKY interaction between the two impurities, indirectly generated by the spin-polarization of the conduction electron sea(s), and (b) $J_e - J_o$, the difference between couplings in the even and odd parity sectors, which governs the amount of conduction electron hybridization between the two sites. (The reflection symmetry of the two-impurity model allows one to classify all electron states as of either even or odd parity. Interactions couple even to even (J_e), odd to odd (J_o) or mix (J_m). The coefficients $J_{e,o}$ depend on impurity spacing, and are equal only at certain separations.)

The single-channel version of this problem [3] (Eq. (1) with $c \equiv 0$) also has these two interactions (a) and (b), but for one channel (in the particle–hole symmetric limit we will be discussing) $J_e - J_o$ renormalizes to zero as temperature is lowered; RKKY/T_K is the only scaling operator. For two channels of electrons, $J_e - J_o$ turns out to be a relevant operator (see Fig. 1 of Ref. [2]); for J_m not too large $J_e \neq J_o$ acts analogously to the channel inequality for the single-impurity problem.

Choosing the form of the asymmetry for the vertical axis of the phase diagram is particularly problematic because of the wide range of choices ($J_e - J_o$; $(J_e - J_o)/(J_e + J_o)$; J_e/J_o; $\sqrt{J_e^2 - J_o^2}$; ...). We first study, along the direction for which RKKY = 0, the crossover temperature T^* between single-impurity behavior and the final even- or odd-parity Kondo state. We vary the asymmetry, and choose the combination which yields the best scaling results for small $J_e - J_o$. We assume

$$T^* \propto (J_e - J_o)^\nu, \quad \nu \text{ some positive exponent.} \qquad (2)$$

We choose T^*, somewhat arbitrarily, as the temperature at which the energy of the first excited state (a spin singlet) relative to the ground state (a spin triplet) reaches one-eighth its value at the even-parity Kondo fixed point (the two states are degenerate at the single-impurity fixed point). In the numerical renormalization group technique the log of temperature is proportional to the iteration number N as $T/D \propto \Lambda^{-(N-1)/2}$, where D is the bandwidth and Λ is a discretization parameter (here $\Lambda = 3$). Thus given Eq. (2), one can conveniently define an associated iteration number N^* such that $N^* = C - (2/\ln\Lambda)\nu\ln(J_e - J_o)$, C a constant. We plot N^* vs $\ln(J_e - J_o)$ in Fig. 1. Surprisingly, the straight-line fit, which is quite good for $J_e - J_o$ not too large, gives a very large scaling exponent $\nu = 10.7 \pm 0.5$. Other forms of the scaling were tried: $(J_o/J_e)^\nu$, $\exp\{-a/(J_e - J_o)\}$, $\exp\{a(J_e - J_o)/(J_e + J_o)\}$, $((J_e - J_o)/J_o)^\nu$, but none fit a straight line as well. An exception was the scaling form $[(J_e - J_o)/(J_e + J_o)]^\nu$, which provided as good a fit. Since the current study has $J_e + J_o$ roughly constant, it does not distinguish between the two scaling forms.

The exponent of roughly 10 implies that for small asymmetry, the crossover from single-impurity behavior only occurs at some very low temperature. However, T^* increases very fast with $J_e - J_o$. One then has a temperature vs $(J_e - J_o)$ phase diagram which is dominated at finite temperatures for small to moderate parity asymmetry by single-impurity multichannel behavior (although at $T = 0$ there is always a one-parity Kondo effect) and which is predominantly Kondo at all temperatures for larger asymmetry between J_e and J_o.

Using $J_e - J_o$ as a vertical axis, one can now proceed to map out a boundary between marginal and Kondo behavior, near the single-impurity limit, taking the relevant perturbations RKKY and $J_e - J_o$ both small but nonzero. This work is in the preliminary stages, and we do not have room for a figure here. However, we can find no region of stability around the single-impurity fixed point. Renormalization flows are either to the one-parity Kondo state (a Fermi liquid), or to the 'marginal' state (a non-Fermi liquid), even for an asymmetry $J_e - J_o$ as small as 0.01, in which case the boundary between low temperature regimes is at $\mathrm{RKKY}/T_K = 0.03$.

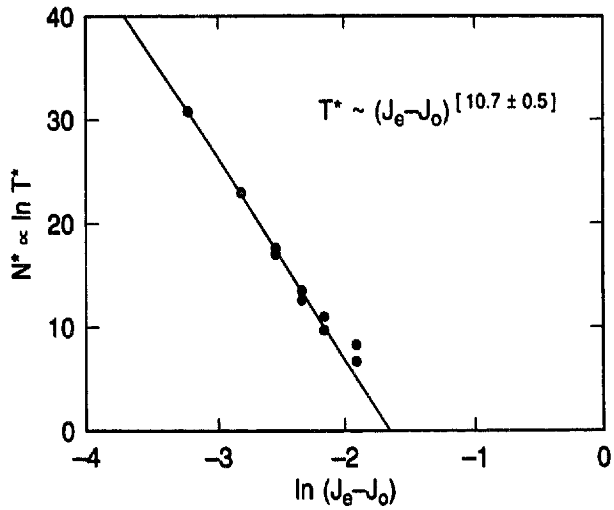

Fig. 1. Log–log plot of crossover temperature T^* vs asymmetry $J_e - J_o$ to determine the scaling exponent. The two sets of points are for even and odd iterations. Best-fit line as shown gives an exponent of approximately ten for scaling away from single-impurity behavior.

In conclusion, it appears that the isolated-impurities ('single-impurity') ground state is intrinsically unstable to RKKY interactions because of its highly spin-degenerate ground state (the four-fold state is easily split into $S = 0$ and $S = 1$ states). Parity asymmetry can act analogously to channel asymmetry to also destabilize the single-impurity state. However, for small even–odd asymmetry the crossover from isolated-impurities to a one-parity Kondo state takes place at very low temperatures. As the asymmetry increases, T^* rises rapidly as $T^* \sim (J_e - J_o)^{10}$. The significance of this large exponent deserves further study.

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