Kondo physics in a dissipative environment

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Abstract

We report nonperturbative results for the interacting quantum-critical behavior in a Bose-Fermi Kondo model describing a spin-$\frac{1}{2}$ coupled both to a fermionic band with a pseudogap density of states and to a dissipative bosonic bath. The model serves as a paradigm for studying the interplay between Kondo physics and low-energy dissipative modes in strongly correlated systems.

Key words: Impurity quantum phase transitions, Kondo effect, pseudogap Bose-Fermi Kondo model, renormalization-group methods
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1. Introduction

Impurity quantum phase transitions (QPTs) and associated local non-Fermi liquid behavior [1] presently receive much attention in connection with tunable quantum criticality in mesoscopic devices, the physics of nonmagnetic impurities in cuprate superconductors, and (via dynamical mean-field theory and its extensions [2]) heavy-fermion quantum criticality. Impurity QPTs have been studied in several models involving fermionic and/or bosonic baths. In the pseudogap Kondo model [3], for example, a depletion of the electronic density of states around the Fermi level can destroy the Kondo effect that is ubiquitous for metallic hosts. In the Bose-Fermi Kondo model (BFKM), the Kondo effect is destroyed by a competing coupling of the impurity spin to a dissipative bosonic bath representing collective excitations of the environment [4,5].

In this work, we study band depletion and dissipation effects together in a *pseudogap* BFKM. The Ising-symmetry BFKM Hamiltonian is

$$\hat{H} = \sum_{\boldsymbol{k},\sigma} \epsilon_{\boldsymbol{k}} c^{\dagger}_{\boldsymbol{k}\sigma} c_{\boldsymbol{k}\sigma} + \tfrac{1}{2} J_0 \boldsymbol{S} \cdot \sum_{\boldsymbol{k},\boldsymbol{k}',\sigma,\sigma'} c^{\dagger}_{\boldsymbol{k}\sigma} \boldsymbol{\sigma}_{\sigma\sigma'} c_{\boldsymbol{k}'\sigma'} + \sum_{\boldsymbol{q}} \omega_{\boldsymbol{q}} \phi^{\dagger}_{\boldsymbol{q}} \phi_{\boldsymbol{q}} + g_0 S_z \sum_{\boldsymbol{q}} (\phi_{\boldsymbol{q}} + \phi^{\dagger}_{-\boldsymbol{q}}). \tag{1}$$

J_0 is the local Kondo exchange coupling between a local spin-$\frac{1}{2}$ $\boldsymbol{S}$ and the fermionic band, while the dissipation strength g_0 couples S_z to a bath of bosonic oscillators characterized by a power-law density of states

$$\eta(\omega) = \sum_{\boldsymbol{q}} \delta(\omega - \omega_{\boldsymbol{q}}) = \frac{K_0^2}{\pi} \left(\frac{\omega}{\omega_0}\right)^s \Theta(\omega)\Theta(\omega_0 - \omega). \tag{2}$$

In the pseudogap BFKM, the fermionic density of states has a power-law pseudogap at the Fermi level ($\epsilon = 0$):

$$\rho(\epsilon) = \sum_{\boldsymbol{k}} \delta(\epsilon - \epsilon_{\boldsymbol{k}}) = \rho_0 \left|\frac{\epsilon}{D}\right|^r \Theta(D - |\epsilon|). \tag{3}$$

For convenience, we set $D = \omega_0 = 1$, in which case the model is fully specified by the exponents r and s and by the dimensionless couplings $J \equiv \rho_0 J_0 \geq 0$ and $g \equiv |K_0 g_0|$.

The pseudogap BFKM with isotropic couplings to the bosonic bath has been studied via perturbative RG methods [6]. Such methods break down for Ising bosonic couplings, where (for $r = 0$ at least), the critical physics occurs at large J and g. We therefore treat Eq. (1) nonperturbatively using a recent extension of the numerical RG [5].

2. Results

RG flows: Figure 1 shows the qualitative dependence of the RG flows on the exponents $r \geq 0$ and $s > 0$. With $g = 0$, Eqs. (1) and (3) describe the pseudogap Kondo model. For $0 < r < \frac{1}{2}$, the stable Kondo fixed point (K) is reached only for $J > J_c(g = 0)$. For $J < J_c(0)$, flow is towards the free-impurity fixed point (FI, shown as a square in Fig. 1) at which the impurity decouples from the baths. The transition between the K and FI phases occurs

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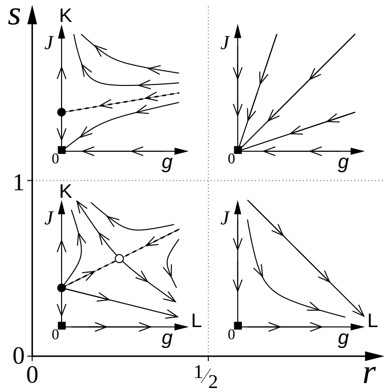

Fig. 1. Schematic RG flows in four regions of the plane spanned by the band exponent r and the bath exponent s. See text for discussion.

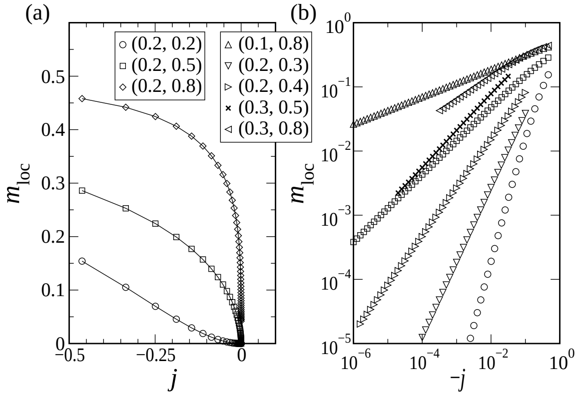

Fig. 2. Order parameter $m_{\rm loc}(j)$ (defined in text) versus $j = J/J_c - 1$ for the (r, s) pairs identified in the legend.

at the fermionic critical point (FC, solid circle in Fig. 1), with properties that are well understood. For $r \to 0^+$, FC merges with FI and the impurity spin is Kondo screened for all $J > 0$. By contrast, FC merges with K as $r \to \frac{1}{2}^-$, and Kondo physics is inaccessible for $r \geq \frac{1}{2}$ [7].

For $g > 0$ and $s < 1$, the RG flow for small J is instead towards the localized fixed point (L), at which the impurity dynamics are controlled by the dissipative bath. For $s < 1$ and $0 \leq r < \frac{1}{2}$, a continuous QPT between the K and L takes place at a second critical point (BFC, open circle in Fig. 1) lying on the separatrix $J_c(g)$ (dashed line in Fig. 1).

The effects of dissipation lessen with increasing s: as $s \to 1^-$, BFC merges with FC, and for $s > 1$ the essential physics is that of the pseudogap Kondo model. Increasing r inhibits Kondo screening: as $r \to \frac{1}{2}^-$, BFC merges with K; for $r > \frac{1}{2}$ and $s < 1$, the RG flow is towards L for any nonzero g.

Local magnetic response: The critical properties of the pseudogap BFKM reveal themselves most clearly in the response to a local magnetic field h that acts only on the impurity spin through an additional Hamiltonian term hS_z. The critical behavior at FC has been reported in [8].

Near BFC, the imaginary part of the local dynamical susceptibility obeys the scaling form characteristic of an interacting critical fixed point:

$$\chi''_{\rm loc}(\omega, T) = T^{\eta-1}\, \Phi(\omega/T,\, j/T^{1/\nu}), \tag{4}$$

where $j = J/J_c - 1$ measures the distance to criticality, and the exponent ν governs the vanishing of a crossover scale $T_* \propto |j|^\nu$ above which quantum-critical behavior is observed up to nonuniversal energy scales. We find that the anomalous exponent characterizing critical local-moment fluctuations is $\eta = 1-s$ independent of r, whereas ν exhibits both r and s dependence.

Knowledge of η and ν is sufficient to determine all critical exponents associated with the response to h. Such hyperscaling behavior is expected at an interacting quantum-critical point having an impurity free energy of the form $F_{\rm imp} = T f(j/T^{1/\nu}, |h|/T^b)$. For instance, the local magnetization $m_{\rm loc} = \langle S_z(T=0, h \to 0)\rangle$ serves as the order parameter for the transition. It obeys $m_{\rm loc}(j < 0) \propto (-j)^\beta$, where $2\beta = \nu\eta$ via hyperscaling. Figure 2a shows $m_{\rm loc}$ versus j for fixed band exponent $r = 0.2$ and three values of the bath exponent $0 < s < 1$; in all cases $m_{\rm loc}(j)$ vanishes continuously as $j \to 0^-$, and $m_{\rm loc}(j) = 0$ for $j \geq 0$. It is clear from Fig. 2a, and from the logarithmic plots in Fig 2b, that the critical exponent β exhibits r and s dependence.

Throughout the domain $0 < r < \frac{1}{2}$, $0 < s < 1$, the BFC exponents satisfy hyperscaling relations to within our estimated numerical uncertainty. For example, for $r = 0.2$ and $s = 0.2$, $\eta = 0.8003(5)$, $1/\nu = 0.200(1)$, and $\beta = 2.001(2)$, with parentheses enclosing the uncertainty in the last digit.

3. Summary

We have studied nonperturbatively the critical properties of the impurity quantum phase transition between Kondo-screened and localized-moment phases in the pseudogap Bose-Fermi Kondo model. Critical exponents depend only on the exponents parameterizing the densities of states of the fermionic band and the bosonic bath, and are found to obey hyperscaling relations characteristic of an interacting quantum-critical point. Further details will be discussed in a forthcoming publication.

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