Converting Spin into Charge in a Dissipative Kondo System

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Introduction
Semiconductor quantum dots and single-molecule devices allow systematic study of strongly correlated electrons, including controlled realizations of Kondo physics. However, such systems feature strong electron-phonon coupling, which tends to decohere the entangled Kondo ground state. We have investigated these competing effects within a simple model.

Model
The model Hamiltonian is

\[ H = H_{\text{cond}} + H_{\text{phonon}} + H_{\text{imp}} + H_{\text{int}}, \]

where \( H_{\text{cond}} = \sum_{k,\sigma} \varepsilon_k c_{k\sigma}^\dagger c_{k\sigma} \) represents a noninteracting conduction band, \( H_{\text{phonon}} = \sum_{\mathbf{q}, \sigma} \omega_{\mathbf{q}} \phi_{\mathbf{q}}^\dagger \phi_{\mathbf{q}} \) represents a dissipative phonons bath, \( H_{\text{imp}} = \varepsilon n_{\downarrow} + U n_{\downarrow} n_{\uparrow} \) describes a localized impurity level with occupancy \( n_{\downarrow} = n_{\uparrow} = 0, 1, \text{or } 2 \), and \( H_{\text{int}} = \sum_{\mathbf{k}, \sigma} \left( c_{\mathbf{k}\sigma}^\dagger d_{\sigma} + \text{H.c.} \right) + \lambda (n_{\downarrow} - 1) \sum_{\mathbf{q}} (\phi_{\mathbf{q}}^\dagger + \phi_{\mathbf{q}}) \) captures the hybridization between the impurity and the band, as well as the Holstein coupling of the impurity occupancy to the on-site phonon displacement. The band density of states is taken to be a constant \( \rho_0 \) over a range \( D \) about the Fermi energy, while the bath spectrum is assumed to take the power-law form

\[ \omega_{\mathbf{q}} = \frac{\omega_0}{1 + \omega_0^s}. \]

Results and Discussion
The electron-phonon coupling \( \lambda \) lowers the \( n_{\downarrow} = 0, 2 \) impurity energies relative to the \( n_{\downarrow} = 1 \) states, renormalizing the on-site interaction at energy or frequency \( \omega < \Omega \) to

\[ U_{\text{eff}}(\omega) = U - 2 \lambda \omega \left[ 1 - \left( \omega / \Omega \right)^s \right]. \]

With increasing \( \lambda \), the conventional (spin-sector) Kondo effect evolves into a charge Kondo effect, as shown by the suppression of the impurity contribution to the static spin susceptibility and the enhancement of its charge counterpart (Figs. 1 and 2). The width of the Kondo resonance reaches a maximum around \( \lambda = \lambda_c \), such that \( \lambda = \lambda_c, \omega \to 0 \) (Fig. 2).

At particle-hole symmetry and for sub-Ohmic bath exponents \( 0 < s < 1 \), further increase in \( \lambda \) drives the Kondo scale to zero at \( \lambda = \lambda_c \), where there is a continuous zero-temperature (\( T = 0 \)) phase transition to a phase in which \( \langle n_{\downarrow} \rangle \neq 1 \). The impurity response to a local electric potential exhibits the hyperscaling of exponents and \( \omega / T \) scaling expected at an interacting critical point. For the Ohmic case \( s = 1 \), the transition is instead of Kosterlitz-Thouless type. Away from particle-hole symmetry, the quantum phase transition is replaced by a smooth crossover but signatures of the symmetric quantum critical point remain in the physical properties at elevated temperatures and/or frequencies.

Conclusions
This example shows that electron-phonon coupling can profoundly affect the properties of nanoscale Kondo systems, transforming spin correlations into charge correlations and creating new \( T = 0 \) phases.

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References