Physica B 312–313 (2002) 167–168
PHYSICA B
www.elsevier.com/locate/physb

Screening effects in Kondo lattices with quenched disorder

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Abstract

We study the competition between the Kondo effect and frozen spin order in the Ising-like spin glass (SG) described by a Kondo lattice (KL) model with quenched disorder. We show that the screening of both diagonal and off-diagonal elements of Parisi matrix shows up at the time scale of the order of magnitude of inverse Kondo temperature. As a result, the freezing temperature is strongly suppressed when Ising and Kondo interactions become comparable. We present a Doniach-like diagram for disordered magnets. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Kondo lattice; Heavy fermions; Spin glass

The problem of competition between Kondo screening of localized spins by conduction electrons and ordering of these spins due to Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction has a long history in the theory of strongly correlated electrons [1]. The Doniach diagram [1] typically describes the transition between paramagnetic (PM) and antiferromagnetically ordered (AFM) metallic states in heavy fermion compounds. In this case there are two possibilities: the compound has long-range magnetic order at low temperatures when RKKY interaction I_{RKKY} is sufficiently large compared with Kondo interaction characterized by the energy scale of Kondo temperature T_{K}, or the compound remains paramagnetic due to quenching of magnetic moments of localized spins in the opposite case. The arguments similar to those used by Doniach can be attributed to disordered magnetic systems, where competition arises between the Kondo effect and spin glass transition due to bond RKKY disorder [2]. As is pointed out in Ref. [3], the presence of nonmagnetic impurities makes the RKKY exchange a random interaction even in the case of regular arrangement of magnetic moments. In this paper we consider the mechanism of suppressing the SG transition due to Kondo screening effects in disordered environment in the domain of parameters $I_{\mathrm{RKKY}} \sim T_{\mathrm{K}}$.

The Hamiltonian of the KL model with quenched disorder is determined by $H = \sum_{k\sigma} \varepsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J\sum_j (\mathbf{S}_j \mathbf{s}_j + \frac{1}{4}N_j n_j) + \sum_{jl} I_{jl}\mathbf{S}_j\mathbf{S}_l$. Here $n_{\mathbf{j}} = \sum_\sigma c^{\dagger}_{\mathbf{j}\sigma} c_{\mathbf{j}\sigma}$ and $\mathbf{s}_{\mathbf{j}} = \sum_\sigma \frac{1}{2} c^{\dagger}_{\mathbf{j}\sigma} \tau_{\sigma\sigma'} c_{\mathbf{j}\sigma'}$, where τ are the Pauli matrices and $c_{\mathbf{j}\sigma} = \sum_{\mathbf{k}} c_{\mathbf{k}\sigma} \exp(\mathrm{i}\mathbf{k}\mathbf{R}_j)$. We consider the Ising-like infinite range spin–spin interaction which corresponds to Sherrington–Kirkpatrick (SK) model [4]. Quenched independent random variables I_{jl} are distributed in accordance with $P(I_{ij}) \sim \exp(-I_{ij}^2 N/(2I^2))$. The spin $S = \frac{1}{2}$ operators are represented as bilinear combinations of semi-fermion operators $S^z_{\mathbf{j}} = (f^{\dagger}_{\mathbf{j}\uparrow} f_{\mathbf{j}\uparrow} - f^{\dagger}_{\mathbf{j}\downarrow} f_{\mathbf{j}\downarrow})/2$, $S^+_{\mathbf{j}} = f^{\dagger}_{\mathbf{j}\uparrow} f_{\mathbf{j}\downarrow}$, $S^-_{\mathbf{j}} = f^{\dagger}_{\mathbf{j}\downarrow} f_{\mathbf{j}\uparrow}$. These operators obey the constraint $N_{\mathbf{j}} = \sum_\sigma f^{\dagger}_{\mathbf{j}\sigma} f_{\mathbf{j}\sigma} = 1$. According to Ref. [5], the constraint is taken into account by introducing the imaginary chemical potential $-\mathrm{i}\pi T/2$ for semi-fermions without changing the spin part of partition function Z,

$$\langle Z^n \rangle_{\mathrm{av}} = \prod \int \mathrm{d}I_{ij} P(I_{ij}) \prod D\{c^a_{i,\sigma} f^a_{i,\sigma}\} \exp\left(\mathrm{A}_0[c^a, f^a] - \int_0^\beta \mathrm{d}\tau H_{\mathrm{int}}(\tau)\right)$$

where A_0 is the action for noninteracting fermions and semi-fermions, and standard replica trick with $a = 1, \ldots, n$ is performed. To construct the Doniach-like diagram describing the interplay between SG ordering and Kondo screening, we calculate the free energy F in a

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[1] This work is supported by SFB-410, MNK acknowledges the support of the Alexander von Humboldt Foundation.

PII: S0921-4526(01)01324-2

replica symmetrical case [6]. To facilitate the calculations we introduce the Edwards–Anderson order parameter $q = \lim_{n\to 0} \langle S_i^\alpha(0) S_i^\beta(t) \rangle$, where $\alpha \neq \beta$ and $t \to \infty$. Nevertheless, due to dynamics induced by inelastic Kondo scattering, the model is not classical anymore, and the second-order parameter $\tilde{q} = \lim_{n\to 0} \langle S_i^\alpha(0) S_i^\alpha(t) \rangle$ should be taken into account. The order parameters q and $\tilde{q}$ are off-diagonal and diagonal elements of Parisi matrix, respectively. As it is shown in Ref. [6], the KL problem with quenched disorder can be mapped onto effective one-cite Kondo problem in effective replica-dependent magnetic field. As a result, the free energy per unit cell in the limit $n \to 0$ is given by

$$\mathrm{F} = \frac{I^2}{4T}[\tilde{q}^2 - q^2] - T \int_x^G \ln \mathrm{C},$$

where $\int_x^G f(x)$ denotes $\int_{-\infty}^{\infty} \mathrm{d}x/\sqrt{2\pi} \exp(-x^2/2) f(x)$, and new equations for the elements of Parisi matrix are

$$\frac{I^2}{2T^2}\tilde{q} = \int_x^G \frac{\partial \ln \mathrm{C}}{\partial \tilde{q}}, \quad \frac{I^2}{2T^2} q = -\int_x^G \frac{\partial \ln \mathrm{C}}{\partial q},$$

$$\mathrm{C} = \int_y^G \frac{2\cosh(h(y,x)/T)}{1 - J\Pi(0, h(y,x))},$$

where $h(y,x) = I(x\sqrt{q} + y\sqrt{\tilde{q} - q})$ is the replica-dependent magnetic field and $J\Pi(0,h) = J/\varepsilon_\mathrm{F} \ln(\varepsilon_\mathrm{F}/\max\{T,h\}) + \mathrm{O}(h^2/T^2)$. The results of numerical solution of these equations are presented in Fig. 1. The simple estimate in high temperature regime $T > T_\mathrm{K}$ reads $\tilde{q} = 1 - c/\ln(T/T_\mathrm{K})$, and the freezing temperature T_f satisfies the inequality $(T_\mathrm{f}/I)^2 = 1 - 2c/\ln(I/T_\mathrm{K}) < 1$. We conclude that the Kondo-scattering results in depression of the SG transition temperature due to screening effects in the same way as magnetic moments and one-site susceptibility in the one-cite Kondo problem. The Kondo screening shows up at large time scale $t \geqslant 1/T_\mathrm{K}$ and affects both diagonal and off-diagonal elements of Parisi matrix. The freezing temperature is strongly suppressed when the Ising and Kondo interactions are of the same order of magnitude.

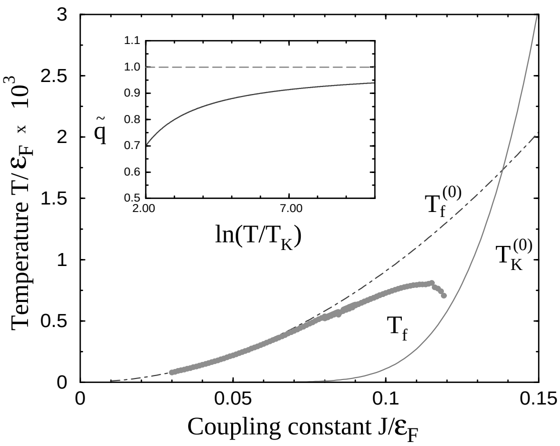

Fig. 1. Doniach diagram for spin-glass transition.

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