The spin glass-antiferromagnetism competition in Kondo-lattice systems in the presence of a transverse applied magnetic field

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Abstract

A theory is proposed to describe the competition among antiferromagnetism (AF), spin glass (SG) and Kondo effect. The model describes two Kondo sublattices with an intrasite Kondo interaction strength \( J_K \) and a random Gaussian interlattice interaction in the presence of a transverse field \( \Gamma \). The \( \Gamma \) field is introduced as a quantum mechanism to produce spin flipping and the random coupling has average \(-2J_0/N\) and variance \(32J_0^2/N\). The path integral formalism with Grassmann fields is used to study this fermionic problem, in which the disorder is treated within the framework of the replica trick. The free energy and the order parameters are obtained using the static ansatz. In this many parameters problem, we choose \( J_0/J \approx (J_K/J)^2 \) and \( \Gamma/J \approx (J_K/J)^2 \) to allow a better comparison with the experimental findings. The obtained phase diagram has not only the same sequence as the experimental one for Ce\(_{2-x}\)Au\(_x\)Co\(_3\)Si\(_3\), but mainly, it also shows a qualitative agreement concerning the behavior of the freezing temperature and the Neel temperature which decreases until a Quantum Critical Point (QCP).

The competition between RKKY interaction and Kondo effect has a fundamental role in Ce and U compounds \([1]\). The presence of disorder in alloys can deeply affect such competition and, therefore, it can lead a quite intriguing issue. For instance, the Ce\(_{2-x}\)Co\(_x\)Si\(_3\) alloy has a phase diagram which displays the sequence of phases spin glass (SG), antiferromagnetism (AF) and a Kondo state when the chemical disorder is increased by substituting Co in the cited alloy \([2]\). Moreover, the Neel temperature decreases until reaching a Quantum Critical Point (QCP) at some particular value of the Co content, with no evidence of Non-Fermi Liquid behaviour.

Earlier theoretical effort \([3]\) has studied the competition among spin glass, antiferromagnetism and Kondo effect based on a framework previously introduced to study the presence of SG in disordered Kondo lattice \([4]\). The problem

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has been treated in a mean field level using functional integral formalism. As most important result, a phase diagram which reproduces exactly the experimental sequence of phases of the CeAu$_{1-x}$Co$_x$Si$_3$ has been obtained. Nevertheless, this approach has a fundamental shortcoming, the Neel temperature displays a behaviour entirely distinct from the experimental one, it does not decrease towards a QCP. The problem is that the model proposed in reference [4] lacks a quantum mechanism able to produce spin flipping.

In the present work, this mechanism has been incorporated by adding a transverse field $\Gamma$ to the original model given in Ref. [3]. Recently, this approach has been successfully used to study the SG solution in Kondo lattice [5] or in competition with AF [6]. Therefore, the Hamiltonian is given by

$$H - \mu N = \sum_{p=A,B} (\sum_{i,j} t_{ij} \hat{d}_{i,p,\sigma}^d \hat{d}_{j,p,\sigma} + \sum_{i} \varepsilon_{i} \hat{n}_{i,p}^f + J_{K} \sum_{i} (\hat{S}_{i,p}^z \hat{S}_{i,p}^- + \hat{S}_{i,p}^- \hat{S}_{i,p}^z) + \sum_{i,j} J_{ij} \hat{S}_{i,A}^z \hat{S}_{j,B}^z + 2\Gamma \sum_{i} (\hat{S}_{i,A}^z + \hat{S}_{i,B}^z)$$

(1)

where $i$ and $j$ sums over $N$ sites of each sublattice. The intersite coupling $J_{ij}$ is a random variable following a Gaussian distribution with average $-2J_0/N$ and variance $32J^2/N$. The spin operators are defined as in references [3, 5]. The hopping of the conduction electrons is allowed only inside the same sublattice among localized spins only in distinct sublattices [3]. On the other hand, the hopping of the conduction electrons is allowed only inside the same sublattice [3].

The partition function is treated in the fermionic path integral formalism where the spin operators are represented by Grassmann fields. The free energy is obtained in the static approximation and the replica method is used to average over the random couplings $J_{ij}$. The fundamental tool in the present case, which has allowed us to calculate the partition function, consists in introducing a matrix formalism with a proper mixing of spinors of each sublattice. Further details will be shown elsewhere [7].

The free energy is obtained as:

$$\beta F = \sum_p |\beta J_K| \lambda_p^2 + \frac{\beta^2 J^2 \bar{\chi}_p^0}{2} (\bar{\mathcal{X}}_{p'}^0 + q_{p'})$$

$$-\frac{\beta J_0}{2} m_p m_{p'} - \frac{1}{2} \int_{-\infty}^{\infty} D\xi_\rho \ln \int_{-\infty}^{\infty} Dz_p e^{E(H_p)}$$

(2)

where

$$E(H_p) = \frac{\int_{-\beta D}^{+\beta D} dx}{-\beta D} \ln \{\cosh \frac{x + H_p}{2} + \cosh \sqrt{\Delta}\}$$

(3)

with $\Delta = [(x - \beta H_p)^2/4 + (\beta J_K \lambda_p^2)^2], H_p = \beta \sqrt{\Gamma^2 + h_p^2}$, the internal field $h_p = J_0 \xi_{i,p} + J \sqrt{2} \xi_{i,p} \xi_{i,p'} - J_0 m_{p'} (p \neq p')$ and $Dz = e^{-z^2/2}/\sqrt{2\pi}$. The saddle point equations for $m_p$ (sublattice magnetization), $q_p$ (SG order parameter) and $|\lambda_p|$ (Kondo order parameter) follow directly from equations (2-4). In the present fermionic formulation, the static susceptibility $\chi_p = \beta \bar{\chi}_p$ is an additional saddle point order parameter to be solved with previous ones.

One important point in the present approach is to assume the conjecture that the parameters $J_0/J \approx (J_K/J)^2$ [3] and $\Gamma/J \approx (J_K/J)^2$ [5]. These relationships are introduced to mimic the relation between the Kondo and RKKY interactions. Therefore, an one free parameter ($J_k/J$) theory can be build where
the order parameters solutions are shown in the phase diagram $T/J$ (T is the temperature) versus $J_K/J$ (see Fig. 1) with AF ($m_A = -m_B \neq 0$), SG ($q_A = q_B \neq 0$) and Kondo state ($\lambda_A = \lambda_B \neq 0$) solutions. As one can see in Fig. 1, as long as $J_K/J$ increases, it is found first a SG, and then an AF solution. The emergence of these particular solutions is basically controled by the relationship $J_0/J$. In that range of $J_K/J$, $\Gamma/J$ is also increasing from zero, which implies that the freezing temperature (the SG transition temperature) has a slight decreasing. However, when AF solution appears, $\Gamma/J$ is strong enough to supress magnetic order leading the Neel temperature to a QCP. From now on, the increasing of $J_K/J$ can only produce a Kondo state. If the Co content can be associated with the $J_K/J$, the results shown in Fig. 1 reproduce the basic aspects of the experimental $\text{CeAu}_{1-x}\text{Co}_x\text{Si}_3$ phase diagram concerning the onset of phases and the behavior of the temperature transitions.

To conclude, we present here a mean field theory which has a proper set of parameters ($J_0/J$, $J_K/J$, $\Gamma/J$) in the sense that they can be related in order to capture the essential effects of the disorder in the competition between Kondo and RKKY interactions for the $\text{CeAu}_{1-x}\text{Co}_x\text{Si}_3$ alloy.

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