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Spin-glass freezing in Kondo-lattice compounds in the presence of a random and a transverse magnetic field

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ABSTRACT

The present work studies the effects of a random magnetic field on the competition among Kondo effect, spin glass (SG) phase and ferromagnetic (FE) order in disordered cerium systems such as $CeNi_{1-x}Cu_x$. A Kondo lattice model is used with an intersite disordered interaction J_{ij} between localized Ising spins in the presence of a transverse magnetic field Γ and a longitudinal random magnetic field. The disorders introduced by J_{ij} and the random field follow Gaussian distributions. They are treated within the one-step replica symmetry breaking procedure. The results suggest that the presence of a random field affects strongly the FE and SG phases. It can disrupt the FE order completely and reduces the SG phase region. It can also introduce an independent spin phase that can coexist within the Kondo regime at high Kondo interaction J_k. On the other hand, the Γ field introduces quantum spin fluctuations able to destroy the magnetic order by decreasing the critical temperature towards a quantum critical point. In addition, the Kondo states can only occur at higher J_k values as Γ increases.

There is much interest in the role of disorder in the competition between the Kondo effect and magnetism. There are several reasons for such an interest, as for example the suggestion that the disorder can lead to deviations of Fermi liquid behavior (see Ref. [1] and references therein). Indeed, one well studied subject is the presence of a spin glass-like state due to the disorder, which is in strong competition with the Kondo effect and magnetic order in many cerium or uranium alloys. There have been recently an increasing level of complexity in this problem, but also a considerable progress in both theory [2–6] and experiments; in fact, such a complex behavior has been observed for example in $CeNi_{1-x}Cu_x$ [7], $CePd_{1-x}Rh_x$ [8] or $Ce_2Au_{1-x}Co_xSi_3$ [9] alloys and also in some uranium alloys.

In the case of $CeNi_{1-x}Cu_x$, there are compelling evidences indicating that the role of disorder seems to be very puzzling. For x small, the Kondo effect is dominant [7]. However, for intermediate Cu doping ($0.3 < x < 0.6$), when the temperature is decreasing, first there is a spin cluster formation, then there is the onset of a spin-glass-like state. Finally, below the freezing temperature, the system evolves to a ferromagnetic phase, also with clusters which become more ferromagnetic with decreasing temperature [10]. Moreover, the hysteresis cycles exhibit sharp macroscopic jumps in the magnetization at very low temperatures [11]. Recently, these jumps in the hysteresis cycles have been well accounted by a model of ferromagnetic vector spins separated in clusters with a large anisotropy [11,12]. More important, the anisotropy must be random. It is well known that vector spin models with very large random anisotropies in the presence of an applied uniform magnetic field can be mapped in the Ising model with random fields [13,14]. Therefore this is an indication that a proper description for the global behavior of $CeNi_{1-x}Cu_x$ alloys could include not only randomness in the exchange interaction and Kondo effect, but also random fields. In fact, the presence of this particular type of disorder, i.e. random fields, has not received attention at all in most of the literature dedicated to study the interplay between Kondo effect and disordered magnetism.

For instance, the interplay among Kondo effect, spin glass (SG) and ferromagnetism (FE) or antiferromagnetism has been extensively studied using a Kondo lattice model with a random exchange interaction J_{ij} between localized f-spins. From this starting point, several different situations have been considered which included also clusters of localized f-spins instead of canonical ones [2–6]. Particularly, the competition between Kondo effect, SG-type state and FE has been investigated using distinct types of random exchange interactions as, for example, the Sherrington–Kirkpatrick (SK) model [2,3], the van Hemmen model [6] and the generalized Mattis model [4]. Nevertheless, the disorder in these studies has been introduced only in the random exchange interaction between the localized f-spins.

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The purpose of the present paper is to study the effect of a random magnetic field on the competition between the Kondo effect, the canonical SG phase and the FE order. The model used is the Kondo lattice model with a random intersite Ising-type interaction between localized f-spins. It is added to a longitudinal random magnetic field and a transverse uniform magnetic field [3]. The model can be obtained from the intrasite exchange interaction that in the mean-field level is able to produce both the Kondo effect and the RKKY interaction [15]. According to the previous works [2–6] an Ising parametrization for the localized f-spins gives adequate results. However, a transverse magnetic field is adopted to play a role similar to the spin flipping part of the Heisenberg model [3]. Here we assume disordered intersite exchange interactions between localized f-spins as in the SK model [16]. For the random magnetic field, it is considered a Gaussian distribution with width Δ and average zero. The disorders are treated using the replica method and the problem is solved within the static approximation [17]. The replica method is analyzed within the one-step replica symmetry breaking scheme [18].

Indeed, one consequence expected from the presence of the longitudinal random field in the problem would be to disrupt any magnetic long range order solution. In particular, for the Ising model with infinite range ferromagnetic interactions, the presence of random field can depress the Curie temperature T_c [19]. When disorder is present as in the classical SK model, the random field can have a double role [20]. It also depresses the freezing temperature T_f. However, the presence of a random field also allows to find a SG solution for the weakest levels of frustration. The presence of a transverse uniform field can disrupt a magnetic long range order. But, the corresponding mechanism (spin flipping) is completely different from the one related to the random fields.

The paper is structured as follows: in Section 1 we find the free energy within 1S-RSB scheme. In Section 2, the saddle point equations for the magnetic and Kondo order parameters are numerically solved and we present a detailed discussion of the phase diagrams. Section 3 is reserved for the final remarks.

1. Model

The Hamiltonian is a Kondo lattice one in which a random coupling J_{ij} is added between localized magnetic moments, a transverse field Γ and a random one h_i as shown below:

$$H=\sum_{k,\sigma}\epsilon_k\hat{n}^d_{k\sigma}+\epsilon_0\sum_{i,\sigma}\hat{n}^f_{i\sigma}+J_k\sum_i[\hat{S}^+_{fi}\hat{s}^-_{di}+\hat{S}^-_{fi}\hat{s}^+_{di}]-\sum_{i,j}J_{ij}\hat{S}^z_{fi}\hat{S}^z_{fj}-2\Gamma\sum_i\hat{S}^x_{fi}-2\sum_i h_i\hat{S}^z_{fi} \quad (1)$$

with $J_k>0$. In Eq. (1), $\hat{S}^z_{fi}=\frac{1}{2}[\hat{n}^f_{i\uparrow}-\hat{n}^f_{i\downarrow}]$, $\hat{S}^+_{fi}=f^\dagger_{i\uparrow}f_{i\downarrow}$, $\hat{S}^-_{fi}=(\hat{S}^+_{fi})^\dagger$, $\hat{S}^x_{fi}=\frac{1}{2}[f^\dagger_{i\uparrow}f_{i\downarrow}+f^\dagger_{i\downarrow}f_{i\uparrow}]$, $\hat{s}^+_{di}=d^\dagger_{i\uparrow}d_{i\downarrow}$, $\hat{s}^-_{di}=(\hat{s}^+_{si})^\dagger$, $\hat{n}^f_{i\sigma}=f^\dagger_{i\sigma}f_{i\sigma}$, $\hat{n}^d_{i\sigma}=d^\dagger_{i\sigma}d_{i\sigma}$ where $f^\dagger_{i\sigma}(f_{i\sigma})$ and $d^\dagger_{i\sigma}(d_{i\sigma})$ are fermionic creation (destruction) operators of f and d electrons, respectively. The spin projections are indicated by $\sigma=\uparrow$ or $\downarrow$. The energies ϵ_0 and ϵ_k are referred to the chemical potentials μ_f and μ_d, respectively.

The coupling J_{ij} and the field h_i in Eq. (1) are random variables following Gaussian independent probability distributions

$$P(J_{ij})=\left[\frac{N}{32\pi J^2}\right]^{1/2}\exp\left[-\frac{N}{32J^2}\left(J_{ij}-\frac{2J_0}{N}\right)^2\right], \quad (2)$$

$$\mathcal{P}(h_i)=\left[\frac{1}{2\pi\Delta^2}\right]^{1/2}\exp\left[-\frac{h_i^2}{2\Delta^2}\right]. \quad (3)$$

From now on, we follow closely the procedure introduced in Refs. [2,3]. The partition function is obtained within the path integral formalism using two types of Grassmann variables associated to localized electrons $(\psi(\omega))$ and conduction ones $(\varphi(\omega))$. Therefore

$$Z=\int D(\psi^\dagger\psi)D(\varphi^\dagger\varphi)e^{[A_0+A_K+A_{dis}]}. \quad (4)$$

The actions in Eq. (4) are given as

$$A_0=\sum_\omega\sum_{i,j}[\underline{\psi}^\dagger_i(\omega)(i\omega-\beta\varepsilon_0+\beta\Gamma\underline{\sigma}_x)\delta_{ij}\underline{\psi}_i(\omega)+\underline{\varphi}^\dagger_i(\omega)[i\omega\delta_{ij}-\beta t_{ij}]\underline{\varphi}_j(\omega)], \quad (5)$$

$$A_K^{stat}\approx\frac{J_k}{N}\sum_{i\sigma}\sum_\omega[\varphi^\dagger_{i-\sigma}(\omega)\psi_{i-\sigma}(\omega)]\times\sum_{j\sigma}\sum_{\omega'}[\psi^\dagger_{j\sigma}(\omega')\varphi_{j\sigma}(\omega')] \quad (6)$$

and

$$A_{dis}^{stat}=\sum_{ij}J_{ij}S_iS_j+2\sum_i h_iS_i \quad (7)$$

where t_{ij} represents the d electron hopping energy, $S_i\equiv S^z_{fi}=\frac{1}{2}\sum_\omega\underline{\psi}^\dagger_i(\omega)\underline{\sigma}^z\psi_i(\omega)$ with the static approximation (SA) [17] used in A_K and A_{dis}. The actions A_0 and A^{stat}_{dis} are written in terms of spinors

$$\underline{\varphi}_i(\omega)=\begin{pmatrix}\varphi_{i\uparrow}(\omega)\\ \varphi_{i\downarrow}(\omega)\end{pmatrix},\quad \underline{\psi}_i(\omega)=\begin{pmatrix}\psi_{i\uparrow}(\omega)\\ \psi_{i\downarrow}(\omega)\end{pmatrix} \quad (8)$$

and the Pauli matrices $\underline{\sigma}^x$ and $\underline{\sigma}^z$.

Following the same procedure as Ref. [3], the Kondo order parameters $\lambda_\sigma=(1/N)\sum_{j,\omega}\langle\psi^\dagger_{j\sigma}(\omega)\varphi_{j\sigma}(\omega)\rangle$ and $\lambda^\dagger_\sigma=(1/N)\sum_{j,\omega}\langle\varphi^\dagger_{j\sigma}(\omega)\psi_{j\sigma}(\omega)\rangle$ are introduced in the partition function Z. In a mean-field level these order parameters describe the correlations $\lambda\approx\lambda_\sigma=\langle f^\dagger_\sigma d_\sigma\rangle$ and $\lambda^\dagger\approx\lambda^\dagger_\sigma=\langle d^\dagger_\sigma f_\sigma\rangle$. Then, the φ fields are integrated out. As a result, the free energy is given by

$$\beta F=2\beta J_k\lambda^\dagger_\sigma\lambda_\sigma-\lim_{n\to 0}\frac{1}{Nn}(\langle\langle Z^n(\{J_{ij}\},\{h_i\})\rangle\rangle_{J,h}-1) \quad (9)$$

where Z^n is the replicated partition function. The disorder present in the problem can be now averaged using Eqs. (2) and (3) as below:

$$\overline{Z}^n=\langle\langle Z^n(\{J_{ij}\},\{h_i\})\rangle\rangle_{J,h}=\int\prod_{i,j}[dJ_{ij}P(J_{ij})]\prod_i[dh_i\mathcal{P}(h_i)]Z^n(\{J_{ij}\},\{h_i\}). \quad (10)$$

The spin glass order parameter $q_{\alpha\beta}$ is introduced using the same procedure of Refs. [2,3,22]. Therefore, one has

$$\overline{Z}^n=\int\prod_{\alpha,\beta}Dq_{\alpha,\beta}\int\prod_\alpha Dm_\alpha\Lambda(q_{\alpha\beta},m_\alpha)\times\exp\left[-N\left(\frac{\beta^2J^2}{2}\sum_{\alpha,\beta}q^2_{\alpha,\beta}+\frac{\beta J_0}{2}\sum_\alpha m^2_\alpha\right)\right] \quad (11)$$

with

$$\Lambda(q_{\alpha\beta},m_\alpha)=\int D(\psi^\dagger_\alpha(\omega)\psi_\alpha(\omega))\times\exp\left[\sum_{i,j}\sum_{\omega,\sigma,\alpha}\psi^\dagger_{i,\sigma,\alpha}(\omega)g^{-1}_{ij}(\omega)\psi_{i,\sigma,\alpha}(\omega)+\sum_{\alpha,\beta}4\beta^2J^2q_{\alpha\beta}+\beta^2\Delta^2)\left(\sum_i S^\alpha_iS^\beta_i\right)+\sum_{i,\alpha}2\beta J_0m_\alpha S^\alpha_i\right] \quad (12)$$

where the inverse Green function $g^{-1}_{ij}(\omega)$ in Eq. (12) is given as

$$g^{-1}_{ij}(\omega)=(i\omega-\beta\epsilon_0)\delta_{ij}-\beta^2J_k^2\lambda^\dagger\lambda\gamma_{ij}(\omega) \quad (13)$$

where $\gamma^{-1}_{ij}(\omega)=i\omega\delta_{ij}-\beta t_{ij}$.