A theoretical study of the spin glass-Kondo-magnetic disordered alloys in the presence of a random field.

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Abstract.

We study here the influence of a random applied magnetic field on the competition between the Kondo effect, the spin glass phase and a ferromagnetic order in disordered cerium systems such as \(CeNi_{1-x}Cu_x\). The model used here takes an intrasite Kondo coupling and an intersite random coupling; both the intersite random coupling and the random magnetic field are described within the Sherrington-Kirkpatrick model and the one-step replica symmetry breaking procedure is also used here. We present phase diagrams giving Temperature versus the Kondo exchange parameter and the random magnetic field makes decrease particularly the importance of the spin glass and ferromagnetic phases.

1. Introduction

The competition between the Kondo effect, a magnetic order (ferromagnetic or antiferromagnetic) and the spin glass state has been extensively studied from both an experimental and a theoretical point of view. Such a competition has been observed in \(CeNi_{1-x}Cu_x\) \cite{1} or \(CePd_{1-x}Rh_x\) \cite{2} alloys. A transition from a cluster spin glass state to an inhomogeneous ferromagnetic phase has been observed at very low temperatures in \(CeNi_{1-x}Cu_x\) alloys \cite{3}. On the other hand, a phase diagram giving Kondo, ferromagnetic and spin glass phases has been deduced from a theoretical point of view where the random intersite exchange interaction is described by the Sherrington-Kirkpatrick model \cite{4} or recently by the van-Hemmen one \cite{5}.

However, some cerium systems, like \(CeNi_{1-x}Cu_x\) alloys, exhibit hysteresis cycles with sharp macroscopic jumps in the magnetization at very low temperatures \cite{6}. The effect is attributed to the formation of clusters in which there is competition between a random anisotropy and the intercluster exchange. Recently, it has been suggested that this result could be modelled by the presence of random magnetic fields applied in such clusters \cite{6}. Therefore, besides the presence of disorder related with cluster spin glass formation, it would be possible to have a new form of disorder in the problem given by the random field which would not increase the frustration in the problem. As a conclusion, \(CeNi_{1-x}Cu_x\) would be an example of competition among two types of disorder and Kondo effect.

The purpose of the present paper is to study the effect of a random magnetic field on the competition between the Kondo effect, the spin glass state and the ferromagnetic order \cite{7}. We take here a random distribution within the Sherrington-Kirkpatrick model for both
the intersite exchange interaction and the magnetic field. We determine, as usual, the phase
diagrams Temperature versus the Kondo coupling constant $J_K$ showing the effect of the random
magnetic field.

2. The model

The Hamiltonian describes here a Kondo lattice where we consider a random coupling $J_{ij}$
between localized magnetic moments and a random field $h_i$, in addition to the classical Kondo
term for a spin $S = 1/2$ and an exchange constant $J_K$. We add here a random field with respect
to the classical Hamiltonian that we have used previously [4].

Thus the starting hamiltonian is given by :

$$H = \sum_{i,j,s} t_{ij} d_{is}^\dagger d_{is} + e_0 \sum_{i,s} n_{is} + J_K \sum_i [\hat{S}_{fi}^\dagger \hat{s}_{di}^- + \hat{S}_{fi}^- \hat{s}_{di}^+] - \sum_{i,j} J_{ij} \hat{S}_{fj}^\dagger \hat{S}_{fi} - \sum_i h_i \hat{S}_{fi}^z \tag{1}$$

with $J_K > 0$. In Eq. (1), $\hat{S}_{fi} = \frac{1}{2} [n_{fi}^\dagger - n_{fi}], \hat{s}_{di} = f_{di} \hat{f}_{di}$, $\hat{S}_{fi}^z = (\hat{S}_{fi}^\dagger)^z$, $\hat{s}_{di}^z = (\hat{s}_{di})^z$, $n_{fi}^\dagger = f_{fi}^\dagger f_{fi}$, where $f_{fi}^\dagger$ ($f_{fi}$) and $d_{is}^\dagger$ ($d_{is}$) are fermionic creation (annihilation) operators of $f$ and $d$ electrons, respectively. The spin projections are indicated by $s = \uparrow$ or $\downarrow$. The coupling $J_{ij}$ and
the field $h_i$ are random variables following Gaussian independent probability distributions :

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

$$P(h_i) = \left[ \frac{1}{2\pi \Delta^2} \right]^{1/2} \exp \left[ - \frac{1}{2\Delta^2} (h_i - h_0)^2 \right]. \tag{2} \tag{3}$$

The free energy averaged over the disorder present in the model is obtained as below [7]

$$< < F(\{J_{ij}\}, \{h_i\}) > > _{J,h} = \int \prod_{(i,j)} [dJ_{ij} P(J_{ij})] \times \prod_i [dh_i P(h_i)] f(\{J_{ij}\}, \{h_i\}). \tag{4}$$

The classical replica method is used to perform the average over $J_{ij}$ and $h_i$ in Eq.(4) and the
free energy is, therefore, given by :

$$-\beta F = \lim_{N \to \infty} \lim_{N_h \to 0} \frac{1}{N_h} ( < < Z^n > > _{J,h} - 1), \tag{5}$$

where $Z^n$ is the replicated partition function.

From now on, we follow closely the procedure introduced in Refs. [8, 9]. 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, we can write :

$$Z = \int D(\psi^* \psi) D(\varphi^* \varphi) e^{[A_h + A_K + A_{SG} + A_h]}, \tag{6}$$

The different actions introduced in equation (6) are presented in Refs. [8, 9], except $A_h$ which is introduced here. The detailed calculations will be published elsewhere [11]. The static approximation [10] has been used in the Kondo action $A_K$ and in the spin glass one $A_{SG}$.

The procedure follows closely Refs. [7, 8, 9, 11] and we determine firstly the Kondo and
spin glass order parameters. The Kondo order parameters $\lambda_\sigma \approx \lambda = \frac{1}{N} \sum_j \langle \psi_j^+ (\omega) \varphi_{j\sigma} (\omega) \rangle$ and

$$\lambda_{\sigma} \approx \lambda^1$$
Figure 1. Calculated phase diagrams $T/J$ versus $J_K/J$ for several values of $\Delta$ for (a) $J_0/J = 0$ and (b) $J_0/J = 1.7$.

3. Results and Conclusions

Thus, we have derived the phase diagrams giving the different phases versus temperature and the Kondo parameter $J_K$ for different parameters, in order to study the influence of a random field. We have taken here a gaussian distribution for the intersite spin glass interaction within the Sherrington-Kirkpatrick model, as we have previously done in refs. [4, 8, 9]. In fact, it is a first model, because we have improved in previous papers the description of the Kondo-spin glass cerium systems by taking for the intersite interaction first a generalization of the Mattis model [12] and then the van Hemmen model [5]; in fact, these two recent models give a ferromagnetic phase below the spin glass one in good agreement with experiment in $\text{CeNi}_{1-x}\text{Cu}_x$ [1], while the Sherrington-Kirkpatrick model gives the opposite behavior. Any way, our purpose is firstly to study the influence of the magnetic random field and the phase diagrams presented here will be already interesting from that point of view.

Figure 1 shows the phase diagrams $T/J$ versus $J_K/J$ for several values of the deviation of the random field, i.e. $\Delta$ varying from 0 to a large value. The figure 1(a) describes the case $J_0 = 0$ without a ferromagnetic phase, while the figure 1(b) describes the case with a large $J_0$ value yielding a ferromagnetic phase (FE), a spin glass one (SG), a Kondo phase and a mixed spin glass-ferromagnetic (SG+FE) phase. For instance, in Fig. 1(a) the temperature of the PM/SG phase transition is decreased as $\Delta$ enhances at the same time as the Kondo state appears at higher values of $J_K$. For $J_0/J = 1.7$, the PM, FE and SG+FE are found as temperature decreases for low values of $J_K$. When $\Delta$ enhances, the FE and SG+FE phases are gradually destroyed. However, the FE order is more affected than the SG one by $\Delta$. For example, inset of Fig. 1(b) ($J_0/J = 1.7$ and $\Delta J = 1.0$) exhibits only the SG phase at low temperatures with Kondo state at larger $J_K$.

In conclusion, we see clearly that the disorder introduced by the random magnetic field tends to finally destroy not only the FE phase but also the SG one. Interestingly, in a smaller extend the Kondo state is also affected in the presented case. In other words, our results also indicate that this new form of disorder, i.e. the random magnetic field also disrupts the singlet formation. In our paper, we have obtained a SG phase below the FE one, in contrast with the experimental behaviour observed in $\text{CeNi}_{1-x}\text{Cu}_x$ alloys; but this result is due to the use of the Sherrington-Kirkpatrick model as previously observed [4] and already corrected by taking a generalization of the Mattis model [12] or the van Hemmen model [5]. Any way, the important result of our paper is to show the role of the random magnetic field which tends to destroy the SG and FE phases. Further works are necessary to study in more detail the effect of the random
magnetic field when the problem is formulated in terms of clusters instead of canonical spins [11].

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