FERROMAGNETISM AND SPIN GLASS IN KONDO LATTICE*

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The Kondo lattice model has been analyzed in the presence of a random inter-site interaction among localized spins with non zero mean J_0 and standard deviation J. Following the same framework previously introduced by us, the problem is formulated in the path integral formalism where the spin operators are expressed as bilinear combinations of Grassmann fields. The static approximation and the replica symmetry ansatz have allowed us to solve the problem at a mean field level. The resulting phase diagram displays several phase transitions among a ferromagnetically ordered region, a spin glass one, a mixed phase and a Kondo state depending on J_0, J and its relation with the Kondo interaction coupling J_{K}.

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1. Introduction

The magnetism in strongly correlated f-electron systems has become a source of great interest due to the physics involved [1] like, for instance, quantum phase transitions and Non-Fermi liquid behavior. Recently,

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an experimental magnetic phase diagram of the Kondo $CeNi_{1-x}Cu_x$ compound has been proposed [2] showing the existence of a spin glass like state. At very low temperatures, the phase sequence Ferromagnetism (FM)-Spin Glass (SG)-Kondo has been observed with decreasing x and in the range 0.7–0.2 for x, the sequence FM–SG is obtained with increasing temperature. Quite recently, a model has been introduced [3] to study the interplay between spin glass ordering and a Kondo state using a Kondo lattice model with an intrasite s–f exchange interaction and an intersite long range random interaction of zero mean that couples the localized spins. In the present work, the model mentioned in Ref. [3] has been extended in order to include the proper elements that produce also a ferromagnetic ordering by taking the mean random interaction J_0 to be different from zero. Therefore, the magnetization can be introduced in addition to the other order parameters and solved coupled to them. From this procedure a phase diagram is obtained which contains ferromagnetism, a mixed phase (FM+SG), a spin glass phase and a Kondo state.

2. The model and results

The Hamiltonian is the same of reference [3] but in the present case the random intersite interaction J_{ij} is infinite ranged with a Gaussian distribution where $\langle J_{ij}\rangle = 2J_0/N$ and $\langle J_{ij}^2\rangle = 8J^2/N$. The spin variables $S_{fi}^{(+-)}$, $(s_{ci}^{(+-)})$ and S_{fi}^{z} are bilinear combinations of the creation and destruction operators (see [3]) for localized (conduction) fermions $f_{i\sigma}^{\dagger}$, $f_{i\sigma}$ ($d_{i\sigma}^{\dagger}$,$d_{i\sigma}$) with the spin projection $\sigma =\uparrow$ or $\downarrow$. The partition function is expressed in terms of functional integrals using anticommuting Grassmann variables $\varphi_{i\sigma}(\tau)$ and $\psi_{i\sigma}(\tau)$ associated with the conduction and the localized electrons, respectively. Using the static approximation it is possible to solve the problem in a mean field theory where the Kondo state is described by the complex order parameters where it has been followed the treatment for the Kondo part in the partition function as introduced in Ref. [3], where it was assumed that $\lambda_\sigma^* \approx \lambda^*$ ($\lambda_\sigma \approx \lambda$). We show in Ref. [4] that first the conduction electron degrees of freedom may be integrated out. The free energy of the present disordered fermionic problem can be given by the replica method and the averaged replicated partition function can be linearized by means of the usual Hubbard–Stratonovich transformation. Therefore, the problem can be analyzed within the replica symmetric ansatz where $q_{\alpha\neq\beta} = q$ is the spin glass order parameter, $m_\alpha = m$ is the magnetization and $q_{\alpha\alpha} = q + \overline{\chi}$, ($\overline{\chi} = \chi/\beta$) with χ being the static susceptibility. The resulting functional integral can be performed and the saddle point solution for the free energy is given by:

$$\beta F = 2\beta J_K\lambda^2 + \frac{\beta^2 J^2}{2}\left\{\overline{\chi}^2 + 2\overline{\chi}q\right\} + \frac{\beta J_0}{2}m^2 - \int_{-\infty}^{+\infty} Dz \ln\left[\int_{-\infty}^{+\infty} D\xi e^{E(\xi)}\right], \quad (2.1)$$

where $E(\xi) = 1/(\beta D)\int_{-\beta D}^{+\beta D} dx \ln\{S(\xi,x)\}$, $S(\xi,x) = \cosh(h_x^+) + \cosh(\sqrt{\Delta})$, $\Delta = (h_x^-)^2 + (\beta J_k\lambda)^2$, $h_x^\pm = (h \pm x)/2$, $h(z_i,\xi_i^\alpha) = \beta J_0 m + \beta J\sqrt{2q}z_i + \beta J\sqrt{2\overline{\chi}}\xi_i^\alpha$ and $T = 1/\beta$ is the temperature. It has been assumed a constant density of states for the conduction electron band $\rho(\varepsilon) = 1/(2D)$ for $-D < \varepsilon < D$ and $Dx = (1/\sqrt{2\pi})\, e^{-x^2/2}dx$. The saddle point equations for the order parameters q, m, $\overline{\chi}$ and λ can be found from Eq. (2.1). The Almeida–Thouless line can be found from Ref. [4].

3. Discussion and conclusions

The resulting coupled saddle point equations for the order parameters produce solutions which give a Kondo state and magnetic ordering like ferromagnetism, spin glass and a mixed phase. Therefore, we are be able to build up transition surfaces among these phases in a $T/J \times J_0/J \times J_{\rm K}/J$ space where J is kept constant. Fig. 1 shows the cut in the phase space transversal to the J_0/J axis. For values of J_0/J close to zero (see Fig. 1(a)), the phase diagram resembles the scenario already found in Ref. [3], that is a paramagnetic phase at high temperatures, a spin glass phase below the freezing temperature T_f and a line $J_{\rm K} = J_{\rm K}^c(T)$ separating both phases from a Kondo state. For that situation, the AT line is at T_f and follows the line $J_{\rm K} = J_{\rm K}^c(T)$. As the value of J_0/J is increased (for small $J_{\rm K}/J$) (see Figs. 1(b), 1(c) and 1(d)), the phase diagram starts to show the presence of a ferromagnetic phase which has a transition temperature $T_{\rm c}(J_0)$ increasing with J_0, the AT line and the calculated replica symmetric line $T^*(J_0)$ decreasing with J_0. Nevertheless, the AT line is always above $T^*(J_0)$. In that scenario, for decreasing temperature, first a transition from paramagnetic to a ferromagnetic phase appears followed by a transition from the ferromagnetic to a mixed phase. For some value of J_0/J, the mixed phase finally disappears and that region of the phase diagram is totally occupied by the ferromagnetic phase. For larger values of $J_{\rm K}/J$, the phase diagram goes to a Kondo state, where the transition line $J_{\rm K}^c$(T) does not depend on J_0. At low temperatures, the SG-Kondo line is a first order transition one and so multiple possible solutions for the order parameters can be found. In the case of $J_0/J < 1.46$ the hatched region in Fig. 1(a) displays where these multiple solutions occur. By computing the free energy we have found the thermodynamically stable solutions.

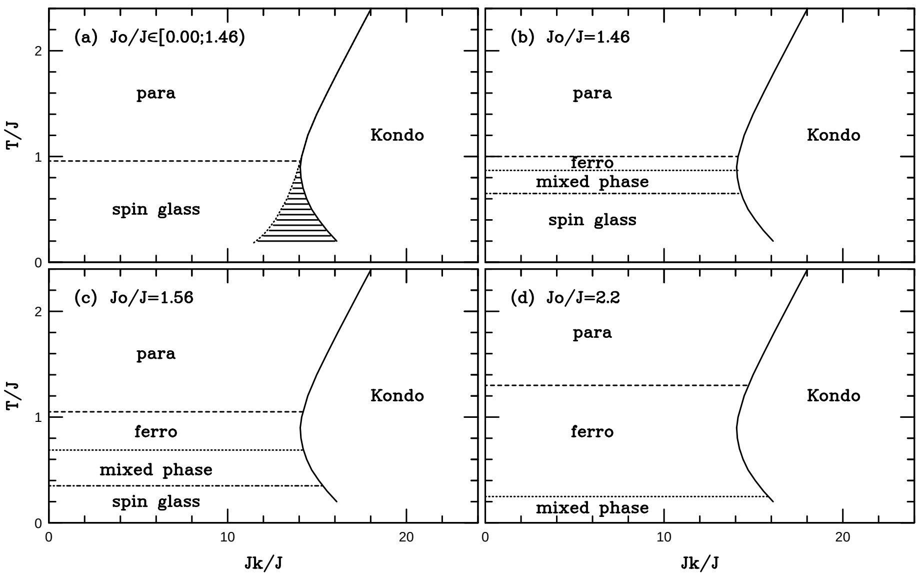

Fig. 1. Cut in the phase transition space transversal to the J_0/J axis for several values of J_0, $J = 0.5$ and $D = 10$.

From the present approach we have been able to generate a quite non-trivial phase diagram with a spin glass phase, ferromagnetism, a Kondo state and a mixed phase. Nevertheless, the calculated spin glass freezing temperature is lower than the Curie temperature in contrast with some experimental findings [2]. However, as pointed out in Ref. [2], a mixed phase cannot be discarded as a possible explanation for the magnetic measurements.

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