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GRIFFITHS PHASES IN THE STRONGLY DISORDERED KONDO NECKLACE* **

T.G. Rappoport, B. Boechat, M.A. Continentino

Departamento de Física, Universidade Federal Fluminense
Av. Litorânea s/n, Niterói, 24210-340, RJ, Brazil

and A. Saguia

Centro Brasileiro de Pesquisas Físicas
Rua Dr. Xavier Sigaud 150, Urca, Rio de Janeiro, 22290-180, RJ, Brazil

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We study the effect of strong disorder on the one-dimensional Kondo necklace model using a perturbative real-space renormalization group approach. The phase diagram of the model presents a random quantum critical point separating two phases; the *random singlet phase* of a quantum disordered XY chain and the *random Kondo phase*. We also consider an anisotropic version of the model which for strong disorder maps on the random transverse field Ising model. These results provide a microscopic basis for non-Fermi liquid behavior in disordered heavy fermions associated with the existence of Griffiths phases.

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1. Introduction

Understanding the effects of randomness on the quantum critical point (QCP) of the $d = 1$ Kondo necklace (KN) model [1] is relevant for the study of disordered heavy fermions systems with non-Fermi liquid behavior [2–4]. Recently we presented a *non-perturbative* real space renormalization group (RG) showing that *weak disorder is an irrelevant perturbation* near the QCP of a $d = 1$, anisotropic, pure KN model [5]. This result is in agreement with the generalized Harris criterion [6, 7] for irrelevance of disorder, $\nu > 2/d$, where $\nu = 2.24$ is the value obtained for the correlation length exponent of

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the QCP of the pure anisotropic system [5]. On the other hand different approaches have been proposed to describe the non-Fermi liquid behavior of disordered heavy fermions that rely on the *relevance* of disorder [2, 3]. Here we investigate the one-dimensional KN model in the case of *strong disorder* using a generalization of a perturbative real space RG approach [8–12].

The one-dimensional KN model is defined by the Hamiltonian,

$$H = \sum_{i=1}^{L-1} W_i({\sigma^x}_i {\sigma^x}_{i+1} + {\sigma^y}_i {\sigma^y}_{i+1}) + \sum_{i=1}^{L-1} J_i \vec{S}_i.\vec{\sigma}_i \,, \tag{1}$$

where σ^μ and S^μ, $\mu = x, y, z$ are spin-1/2 Pauli matrices denoting the conduction electrons and the spins of the local moments, respectively. The sites i and $i+1$ are nearest-neighbors on a chain of L sites. The local Kondo interactions, $J_i > 0$ and the hopping energies $W_i > 0$ are uncorrelated quenched random variables with probability distributions, $P_J(J_i)$ and $P_W(W_i)$. In the anisotropic version of the model, (X-KN), the band of conduction electrons is represented just by an Ising term, $\sum_{i=1}^{L-1} W_i {\sigma^x}_i {\sigma^x}_{i+1}$. The full isotropic KN model in Eq. (1) will be referred from now on as the XY-KN to avoid confusion. For the X-KN there is an unstable fixed point at a finite value of (J/W) separating an antiferromagnetic phase from a spin compensated, Kondo-like phase [5]. For the XY-KN, any interaction $J > 0$ gives rise to a dense Kondo state.

In order to implement the perturbative RG method for the KN models, we consider the conduction electrons σ_i and the local moments S_i arranged in a chain as shown in Fig. 1. Next we choose the largest interaction in the chain,

$$\Omega = \max\{W_i, J_i\} \,. \tag{2}$$

If the strongest interaction is a Kondo coupling (*bond*) between a local moment and a conduction electron, for example, $\Omega_\mathrm{I} = J_2$, the local moment S_2 and the conduction electron σ_2 are decimated out yielding an effective hopping $\tilde{W}$ between the conduction electrons σ_1 and σ_3 at neighboring sites which is obtained in second order perturbation theory (see Fig. 1).

If the strongest interaction is a hopping term, say, $\Omega_\mathrm{I} = W_2$, the four spins σ_2, S_2, σ_3 and S_3 are considered as a *cluster*. This is replaced by an effective two-spin cluster consisting of renormalized, local moment $\tilde{S}$ and conduction electron $\tilde{\sigma}$ coupled by a new effective local Kondo interaction, $\tilde{J}$ (see Fig. 1). Thus, after decimating a strong interaction, W_i or J_i, we have an effective Hamiltonian with two less spin degrees of freedom and all couplings $< \Omega_\mathrm{I}$.

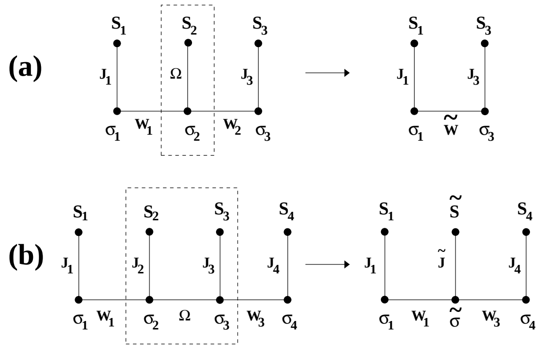

Fig. 1. The decimation processes in the case the strongest interaction Ω is either (a) a bond or (b) a hopping .

The RG transformation gives, in the case the strongest interaction is a bond, an effective hopping,

$$\tilde{W} = \frac{W_1 \; W_2}{\kappa\Omega} \tag{3}$$

and in the case it is a hopping we obtain,

$$\tilde{J} = \frac{J_2 \; J_3}{\kappa\Omega} \,. \tag{4}$$

The new Hamiltonian has exactly the same form as the original one, but now the system is formed by spin clusters and effective bonds. Note that the resulting flow equations, Eqs. (3) and (4), present a duality between W and J. We find that for the X-KN model the parameter $\kappa = 1$, so that the recursion relations for this model map exactly into those of the RTIM [10]. For the XY-KN model, we get $\kappa = 4/\sqrt{6} \approx 1.63$.

2. Results

The method is implemented numerically on samples of sizes up to $L = 2^{18}$ and averages over 10^2 configurations [13]. We use rectangular distributions for the local bonds and hopping terms. Periodic boundary conditions are applied. The relevant parameter is the ratio (J_0/W_0) of the cut-offs of the original distributions. Furthermore we take $W_0 = 1$ such that J_0 is taken as the control parameter. The dual nature of the recursion relations allows to locate the random QCP at $J_0 = 1$ for any κ. We measure the distance to the random QCP by the variable

$$\delta = \frac{\langle \ln J \rangle - \langle \ln W \rangle}{\mathrm{var}(\ln J) + \mathrm{var}(\ln W)} \,, \tag{5}$$

where $\langle - \rangle$ means average over quenched disorder and $\mathrm{var}(x)$ denotes the variance. Of course $\delta = 0$ for $J_0 = 1$. For the anisotropic KN model, the QCP at $J_0 = 1$ separates a disordered antiferromagnetic phase ($J_0 < 1$) from a dense Kondo compensated phase ($J_0 > 1$). Above and below, but close to criticality, the recursion relations in Eqs. (3) and (4), give rise to Griffiths phases with a range $0 < |\delta| < \delta_{\mathrm{G}}$. In each side of the QCP such phases are dominated by rare, very large clusters of the opposite phase. They are also characterized by power law behavior of the probabilities distributions with exponents which depend on the distance δ to the QCP. For $J_0 > 1$, in the strongly disordered regime above the Griffiths phase, we find a random Kondo phase which consists of a collection of isolated singlets with random excitation energies. It is natural to describe such a phase by a model with a distribution of Kondo temperatures [2]. The susceptibility however does not diverge at low temperatures in the RKP. We observe a diverging susceptibility in the case of lower unbound distributions where the Griffiths phase extends all over the disordered region. Consequently our results indicate that a diverging $\chi(T)$ is due to a Griffiths phase. Our approach shows that differently from the case of weak disorder [5], strong disorder is a relevant perturbation and gives rise to Griffiths phases which for distributions with a gap extend over finite regions of the phase diagram, above and below the QCP.

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