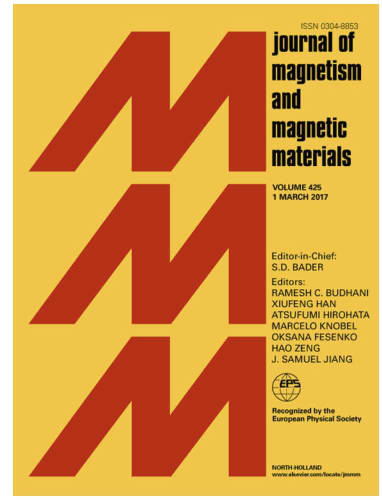


# Aperiodic exchange modulation effect on the specific heat in the Kondo necklace model

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PII: S0304-8853(18)30495-5
DOI: https://doi.org/10.1016/j.jmmm.2018.08.072
Reference: MAGMA 64269

To appear in: *Journal of Magnetism and Magnetic Materials*

# Aperiodic exchange modulation effect on the specific heat in the Kondo necklace model



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(Dated: July 20, 2018)

In the present work we study the effect of the aperiodic exchange modulation on the spin gap at finite temperature as well as the specific heat of the Kondo necklace model in two and three dimensions. For this purpose, we use a representation for the localized and conduction electrons in terms of local Kondo singlet and triplet operators. A decoupling scheme on the double time Green's functions is also used to find the dispersion relation for the excitations of the system. The influence of the aperiodic exchange modulation on the spin gap at low temperatures is discussed in the paramagnetic phase. Moreover, we investigate the specific heat as a function of the aperiodic exchange modulation at low temperatures in two cases: above the quantum critical point i.e., along the so-called *non-Fermi liquid trajectory* and in the Kondo spin liquid state. We have also compared our results with previous bond operator mean-field calculations.

## I. INTRODUCTION

In the last years many studies on the low energy properties of quantum spin systems with modulated spatial structure have been attracting wide interest due to the huge sensitivity to structural details in such systems [1–6]. Even, in real quasicrystalline systems [7] with structural [1, 2] and chemical [8, 9] aperiodicity, the physical properties strongly differ from their related crystalline phases [10, 11]. In this scenario, it has been recently observed a heavy fermion *like* behavior on the $Yb_{15}Al_{34}Au_{51}$ icosahedral quasicrystal compound and its approximant crystal $Yb_{14}Al_{35}Au_{51}$ [12–15], where measurements of the magnetic susceptibility $\chi$ and specific heat $C$ diverge as temperature $T \to 0$ (quantum criticality). Several authors have claimed that this non-Fermi-liquid (NFL) behavior is due to strong correlations of the critical Yb-valence fluctuation and small Brillouin zone (corresponding by large unit cell) [16, 17]. This singular behavior has been studied by using the Anderson impurity model for a single local moment coupled to conduction electrons in an approximant geometry [18]. The main result of this study is that NFL behavior of $\chi$ and $C$ are due to a broad power-law distribution of Kondo temperatures which delays screening of a huge fraction of the magnetic moments until very low temperatures.

In heavy fermion systems two different electrons are mainly found: conduction electrons, corresponding to s and p orbitals that move through the crystalline lattice, and the localized electrons, corresponding to f orbitals. The interaction between these electrons leads to competition between two effects. The first one, the Kondo effect, tends to screen the localized magnetic moment (of f electrons) and generates a nonmagnetic ground state. The second one, called the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction, is an indirect exchange between the magnetic ions, mediated by the conduction electrons, and favors long-range magnetic order. These effects are contained in the Kondo necklace model [19] which neglects charge fluctuations and considers only spin fluctuations. Previous work of the Kondo necklace model (KNM) in one dimensional chain lattices showed that the pure KNM at zero [20] and finite temperature [21], do not present any long-range magnetic order. On the other hand, studies carried out with this model but at higher dimensions indicate that the model presents a quantum critical point (QCP) where the nonmagnetic gapped phase goes to zero and at the same time appears a magnetic gapless phase [22–24]. The KNM was also employed for studying heavy fermion systems under a magnetic field [25, 26], considering thermal and magnetic entanglement [27], dimensional crossover [28, 29], anisotropy [30–33] and recently for studying the role of an aperiodic exchange modulation (chemical aperiodicity) in heavy fermions materials [8].

Thermodynamic quantum critical behavior and physical properties of the KNM have been studied using the bond operator mean-field approximation where analytical relations [22, 30] and numerical results [24, 31, 32, 34] were found close to the QCP, for the spin gap, the critical Néel line, and the specific heat. In this framework, we introduce here an aperiodic modulation, i.e., a Fibonacci sequence, on the antiferromagnetic (AF) Kondo coupling $J_i$ of the finite temperature KNM to study its effects on the specific heat. This study will be done along the so-called NFL trajectory, and in the Kondo spin liquid (KSL) state where the strong coupling limit is well suited. We compare our numerical results in two and three di-