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Competing effective interactions of Dirac electrons in the Spin–Fermion system

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HIGHLIGHTS

- Antiferromagnetic Heisenberg–Kondo lattice model with itinerant Dirac fermions.
- Integrating out the spins generates competing interactions: BCS-like, excitonic and magnetic.
- Novel mechanism of superconductivity from magnetic interactions between the spins and electrons.
- Dome-shaped dependence of the temperature on the chemical potential in agreement with pnictides.

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ABSTRACT

Recently discovered advanced materials, such as heavy fermions, frequently exhibit a rich phase diagram suggesting the presence of different competing interactions. A unified description of the origin of these multiple interactions, albeit very important for the comprehension of such materials is, in general not available. It would be therefore very useful to have a simple model where the common source of different interactions could be possibly traced back. In this work we consider a system consisting in a set of localized spins on a square lattice with antiferromagnetic nearest neighbors interactions and itinerant electrons, which are assumed to be Dirac-like and interact with the localized spins through a Kondo magnetic interaction. This system is conveniently described by the Spin–Fermion model, which we use in order to determine the effective interactions among the itinerant electrons. By integrating out the localized degrees of freedom we obtain a set of different interactions, which includes: a BCS-like superconducting term, a Nambu–Jona-Lasinio-like, excitonic term and a spin–spin

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magnetic term. The resulting phase diagram is investigated by evaluation of the mean-field free-energy as a function of the relevant order parameters. This shows the competition of the above interactions, depending on the temperature, chemical potential and coupling constants.

1. Introduction

Many advanced materials, which were discovered recently, such as heavy fermions and high-Tc superconductors, exhibit a phase diagram so rich that it suggests the presence of different competing interactions as the reason behind the various types of ordering. Abundant experimental data exist for several of these materials. Nevertheless, a clear unifying picture that would allow the understanding of the detailed mechanisms that generate such competing interactions is not yet available. Such a picture, however, could be quite well one of the key requirements for understanding the essential physics of these materials. It could shed light, for instance, on the nature of the mechanisms that produce the onset of high-Tc superconductivity in cuprates and iron pnictides.

In many new materials we find a phase diagram where we can observe, for instance, a deep interplay among superconducting, magnetic and charge orderings. Heavy fermions are the prototype of materials presenting these features [1–4]. They are typically compounds possessing f-electrons belonging to a not completely filled band, which consequently produce an array of localized magnetic moments. These will interact with the itinerant electrons, thereby generating an effective electron mass that is orders of magnitude larger than the free electron mass. Typical examples are the layered compounds $CeMIn_5$ ($M = Co, Ir, Rh$) [5].

If one assumes that the interaction among the localized spins in heavy fermions is mediated by the itinerant electrons one obtains the effective Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction for such spins. These systems are frequently described by the Kondo Lattice model [6], which includes a Kondo interaction between itinerant and localized spins. The physical behavior is determined, to a large extent, by the competition between the Kondo and RKKY interactions, the former tending to screen the latter. Conversely, it happens that for many systems possessing localized spins and itinerant electrons, a super-exchange mechanism would predominate, thereby generating an effective Heisenberg antiferromagnetic interaction among the localized spins. Including the Kondo interaction one obtains now the Spin–Fermion model [7]. This is the model we shall consider here.

Some other materials, which display a rich phase structure, have also attracted a lot of attention recently. Among them are the high-Tc superconductors, namely the cuprates and iron pnictides. The former present localized copper d-electrons in a half-filled band and subject to a super-exchange coupling mediated by p-orbitals of oxygen ions. Now, itinerant electrons are introduced through doping and, eventually, shall undergo a Kondo interaction with the localized spins. In the case of cuprates, therefore, we might expect that the Spin–Fermion model would provide a correct description of the relevant physics. Indeed, this model has been extensively used in the description of cuprates [8–10]. In the case of the pnictides, both the localized and itinerant electrons belong to the d-orbitals of the iron ion. It has been shown [11] that the interaction among the localized spins can be described by a AF Heisenberg-type model with next-to-nearest neighbors interactions. Again, the itinerant electrons are supposed to interact with the localized ones via a Kondo interaction [12,13].

Interestingly, for many of the systems mentioned above it happens that, under different conditions and for different reasons, the electronic excitations behave as Dirac fermions. Iron based pnictide materials, for instance, undergo a transition from a magnetically ordered state to a superconducting one upon doping [14–16]. For the particular case of the 122 materials, magnetic order and superconductivity coexist in a small region of the phase diagram [17] and the new quasiparticles in that region exhibit a Dirac-like linear energy dispersion relation [18,19,11].

In the case of cuprate superconductors the parent compounds are insulators presenting AF order. As charge carriers are added to the CuO_2 planes, there is the onset of superconductivity, with