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Spins, electrons and broken symmetries: Realizations of two-channel Kondo physics

Spins, electrons et symétrie brisée : Réalisation de la physique Kondo à deux canaux

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ABSTRACT

Adding a second Kondo channel to heavy fermion materials reveals new exotic symmetry breaking phases associated with the development of Kondo coherence. In this paper, we review two such phases, the “hastatic order” associated with non-Kramers doublet ground states, where the two-channel nature of the Kondo coupling is guaranteed by virtual valence fluctuations to an excited Kramers doublet, and “composite pair superconductivity,” where the two channels differ by charge $2e$ and can be thought of as virtual valence fluctuations to a pseudo-isospin doublet. The similarities and differences between these two orders will be discussed, along with possible realizations in actinide and rare earth materials like URu_2Si_2 and $NpPd_5Al_2$.

RÉSUMÉ

L’ajout d’un second canal Kondo dans les matériaux à fermions lourds révèle de nouvelles phases exotiques brisant la symétrie et associées au développement de la cohérence Kondo. Nous passons en revue dans cet article deux de ces phases, l’ordre *hastatique* associé à des doublets fondamentaux non Kramers, où la nature double-canal du couplage Kondo est assurée par des fluctuations de valence vers un doublet de Kramers excité, et la « supraconductivité à paire composite », où les deux canaux diffèrent d’une charge $2e$ et peuvent être vus comme des fluctuations de valence virtuelles vers un doublet de pseudo-isospin. Les similarités et différences entre ces deux ordres sont discutées, ainsi que leurs possibles réalisations dans des matériaux à base d’actinides et de terres rares, comme URu_2Si_2 et $NpPd_5Al_2$.

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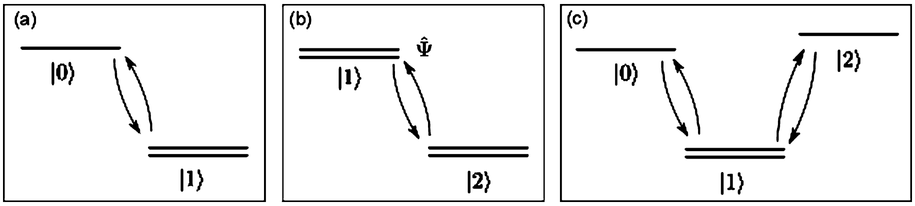

Fig. 1. (a) The usual Kondo effect involves virtual valence fluctuations between a Kramers doublet and an excited singlet state. (b) Hastatic order involves a non-Kramers doublet fluctuating to an excited Kramers doublet. (c) Composite pairing arises when a Kramers doublet fluctuates to two excited singlets whose charge differs by $2e$.

1. Introduction

The interplay of nearly free conduction electrons and localized f-electrons in heavy fermion materials gives rise to a fascinating competition between magnetism and the heavy Fermi liquid resulting from the hybridization of c- and f-electrons [1]. This competition is thought to generate rich phase diagrams containing not only heavy Fermi liquids and magnetically ordered phases [2], but superconductivity and exotic spin liquid phases [3,4]. All of this physics emerges from a single Kondo channel—a single symmetry in which conduction electrons can screen the local moments. When a second Kondo channel is added, the physics is potentially even richer. This new physics is particularly relevant for actinide materials, where the larger 5f orbitals lead to more mixed valency than their rare-earth cousins, with correspondingly higher temperature scales. In this paper we review two exotic new phases proposed to result from the interference of competing screening channels: "hastatic order" associated with the two screening channels of a non-Kramers doublet and "composite pairing" occurring when a Kramers double interacts with two different channels, one hole-like (c) and the other electron-like ($c^\dagger$). Both proposals are motivated by real materials: hastatic order is a possible explanation of the hidden order in URu_2Si_2 [5] and composite pair superconductivity may explain how superconductivity can arise directly out of a Curie paramagnet in certain "115" materials like $CeMIn_5$ ($M = \mathrm{Co, Ir}$) [6,7] and $NpPd_5Al_2$ [8].

Heavy fermion materials contain two species of electrons: nearly free conduction electrons and strongly interacting f-electrons that are localized at high temperatures. The Kondo effect is an antiferromagnetic interaction through which the conduction electrons screen the local moments to form Kondo singlets, giving rise to a heavy Fermi liquid. The Kondo effect can also be thought of as a hybridization between two types of electrons; however, as the f-electrons are strongly interacting, the object hybridizing with the conduction electrons is not the original f-electron, but rather a composite fermion consisting of a conduction electron and a spin flip, $f^\dagger_\uparrow \sim c^\dagger_\downarrow S_+$. In the single-channel Kondo effect, this hybridization is generated by valence fluctuations of the f-ion from a ground state doublet to an excited singlet state, as shown in Fig. 1(a). As the excited singlet carries no quantum numbers, it breaks no symmetries and the Kondo effect develops as a crossover. This process is captured in the single-channel Anderson model,

$$H = \sum_k \epsilon_k c^\dagger_k c_k + V \sum_j \left(c^\dagger_j |0\rangle\langle\sigma| + H.c.\right) + \sum_j \epsilon_f |\sigma\rangle\langle\sigma| \tag{1}$$

where $|0\rangle$ and $|\sigma\rangle$ represent the empty (excited) and singly-occupied (ground) states of the f-ion, and the doubly occupied states, $|2\rangle$ are forbidden. Typically, we solve this model by introducing a slave boson, $b^\dagger|\Omega\rangle$ to represent the excited singlet, $|0\rangle$ and a pseudo-fermion, $f^\dagger_\sigma|\Omega\rangle$ to represent the ground state doublet, $|\sigma\rangle$, where $|\Omega\rangle$ is the particle vacuum [9]. The development of a coherent Kondo effect is then captured by the development of $\langle b\rangle$ at the Kondo temperature, T_K, which decreases the valence, $n_\mathrm{f} = 1 - \langle b\rangle^2$. In this mean field approach, the Kondo effect appears as a phase transition, but as it is not protected by symmetry, gauge fluctuations restore it to a crossover [10].

While the usual Kondo effect involves an excited singlet, the two-channel Kondo effect involves an excited doublet, protected by channel symmetry. The development of Kondo coherence breaks this channel symmetry, causing the coherence to onset at a phase transition rather than a crossover. Typically the channel symmetry will coincide with another physical symmetry; in our two examples, these are time-reversal and particle-hole symmetry. These two symmetries describe the two main classes of two-channel Kondo problems, and can be distinguished by the number of f-electrons. The single-channel Kondo effect typically results from materials with an odd number of f-electrons, where the ground state is guaranteed to be a Kramers doublet, protected by time-reversal symmetry. The excited states contain even numbers of f-electrons and are usually taken to be singlets, unprotected by time-reversal symmetry.

Atoms with even numbers of f-electrons can also have doublet ground states; these non-Kramers doublets are protected by crystal symmetry rather than time-reversal symmetry. Here, valence fluctuations involve excited states with an odd number of f-electrons: Kramers doublets. This scenario is illustrated in Fig. 1(b), where now the two excited states each require a slave boson, $\hat{\psi}_\uparrow$ and $\hat{\psi}_\downarrow$ that can be packaged into a spinor, $\hat{\Psi} = (\hat{\psi}_\uparrow, \hat{\psi}_\downarrow)$. The development of Kondo coherence, $\langle\hat{\Psi}\rangle$ requires the spinor to pick a direction in spin-space, breaking both spin-rotation and time-reversal symmetries. In fact, as here the "order parameter" $\hat{\Psi}$ carries a half-integer spin and behaves as a spinor, the resulting state is more subtle than the conventional, vectorial magnetic order. This spinorial hybridization is what we have termed hastatic order [11]; the primary order parameter is the hybridization gap, but all other symmetry breaking observables are suppressed by T_HO/D,

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