Long range order and two-fluid behavior in heavy electron materials

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 AUTHOR SUMMARY

Heavy-fermion compounds are special metals containing a lattice of localized magnetic moments whose hybridization with the background conduction electrons (see Fig. P1) gives rise to a new quantum state of matter: the heavy-electron Kondo liquid (1, 2). The properties of the Kondo liquid may be determined by combining nuclear magnetic resonance (NMR) Knight shift experiments (the nuclear spin resonance frequency shift arising from the electronic susceptibility) with measurements of the static magnetic susceptibility (3). Below a characteristic temperature the Kondo liquid coexists with the lattice of hybridized local moments, and their subsequent evolution is described phenomenologically by a two-fluid model. However, under the recent work of Yang and Pines (4), we lacked a framework that connects that emergent behavior to the development of ordered states at low temperatures. Here we report detailed new Knight shift measurements for several heavy-electron compounds that confirm the connection they propose between the hybridization strength and emergence of low-temperature order. The measurements provide detailed information on the ordered states of the Kondo liquid in several key heavy fermions and suggest that for weakly hybridizing materials, the approach to a local-moment ground state is always preceded by relocalization.

The interaction between the local moments and conduction electrons in heavy-fermion compounds is sufficiently weak such that at room temperature these two degrees of freedom behave independently of one another. Below a crossover temperature, \( T^* \), the localized and conduction electrons begin to collectively hybridize, giving rise to a fluid of itinerant electrons with an enhanced effective mass (2). This behavior is reflected in various experimental quantities such as the electrical resistivity or magnetic susceptibility. NMR Knight shift measurements offer the best direct probe of the emergent behavior. The nuclear spins of the atoms in these materials experience hyperfine couplings to both the local-moment spin and conduction electron spins (3). In general, these two coupling constants differ from one another, which enables one to measure the magnetic susceptibility independently of the heavy-electron fluid. NMR is the key to separating the contribution from the remaining local moments, which dominate the bulk magnetic susceptibility. We have measured the NMR Knight shift of the heavy-electron fluid in several key materials in order to probe the emergence below \( T^* \) and the influence of long-range order at low temperatures. The heavy-fermion compounds CeCoIn\(_5\) and CeIrIn\(_4\) are prototypical heavy electron superconductors in which hybridization begins at temperatures well above the superconducting transition. Between these two temperatures, the local moments gradually dissolve into the heavy-electron fluid, and the heavy-electron susceptibility increases monotonically as a function of a universal scaling transformation (5).

We find remarkably similar behavior in URu\(_2\)Si\(_2\) at the so-called hidden-order transition temperature. This material has been investigated for more than 20 years and is known to undergo a phase transition at 17.5 K to a state that is not a conventional form of magnetic order (5). The ordered phase is usually referred to as hidden order, because the nature of this phase remains unclear at present. Our data reveals that the universal scaling persists down to the transition temperature with no evidence of any precursor effects.


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temperature. Below this temperature, the susceptibility drops and saturates at a finite value. This behavior suggests that the hidden order develops as a result of an instability of the itinerant heavy-electron fluid in a manner similar to the development of heavy-electron superconductivity.

In contrast to a monotonic increase of hybridization with decreasing temperature, compounds with magnetic ground states exhibit a relocalization of the local moments prior to the development of long-range order. At a temperature between the hybridization temperature and the magnetic ordering transition temperature, the heavy-electron susceptibility exhibits a downturn, indicating that hybridization of the local moments with the conduction electrons reverses its course and is suppressed (see Fig. P1). The ground state that results is not an instability of the hybridized heavy-electron fluid but rather long-range order of the local-moment electron spins. The degree to which the system has hybridized at the transition temperature may vary, in which case the magnitude of the ordered moments can be different from one material to the other.

These findings are important because they elucidate the interplay between the local moments, the heavy-electron fluid, and the nature of the ground state in heavy-electron materials. Not only do they provide us with a more comprehensive interpretation of experimental data, but we now can quantify and correlate the degree of hybridization in various materials with the long range order. Despite their low transition temperatures, heavy-electron superconductors are a model system for research on unconventional superconductivity. Our results suggest that many of the unusual phenomena that they exhibit should be interpreted in light of the two-fluid picture.