Holes in a Kondo lattice

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Real metals invariably contain impurity atoms, and at concentrations of parts per million, nonmagnetic impurities have a barely detectable influence on the electronic properties of the vast majority of metals. On the other hand, pronounced changes can arise from magnetic impurities, such as iron impurity atoms in gold. At room temperature the magnetic moment carried by iron's 3d electrons is decoupled from the electrically conducting electrons of gold and produces a magnetic susceptibility expected for atomic iron moments, but at much lower temperatures the iron moments are compensated exactly by the collective antiferromagnetic alignment of spins carried by conduction electrons. The inherently quantum many-body process of moment compensation, called the Kondo effect (1), builds up a resonance in the electronic density of states (2), giving the conduction electrons a heavy mass. An extreme limit of the Kondo-impurity effect is found in intermetallic compounds that are built structurally from a periodic lattice of 4f- or 5f-electron Kondo atoms, such as cerium or uranium. Except for the very heavy mass of their itinerant charge carriers and the physics that underlies this mass enhancement (3), these Kondo-lattice or heavy-electron metals at very low temperatures are physically equivalent to a simple metal like gold. Writing in PNAS, Hamidian et al. (4) address the question of what happens when a magnetic atom U is replaced by a nonmagnetic impurity atom Th in the Kondo lattice formed in URu_2Si_2. Unlike the negligible influence of Th impurities in gold, the Th defect induces strong nanoscale electronic heterogeneity in URu_2Si_2 that is revealed in spectroscopic images obtained with a scanning tunneling microscope (STM). In effect, the nonmagnetic atom "digs a hole" in the strongly correlated electron state of URu_2Si_2, with consequences that ripple well beyond the immediate vicinity of the impurity. By disrupting the U-lattice periodicity, the nonmagnetic Th atom locally untangles the correlated many-body state of the Kondo lattice and creates a new resonance in the electronic density of states, complementary to the effect of adding a magnetic iron impurity to gold—hence, the term "Kondo-hole." The striking STM images of Hamidian et al. (4) validate recent theoretical predictions (5) of the real-space perturbation of electronic and magnetic correlations introduced by a Kondo-hole. These perturbations, in turn, reveal the physical process that fundamentally distinguishes a Kondo lattice from simply a dense, periodic array of noninteracting Kondo impurities. The intense, widespread electronic heterogeneity induced by Kondo-holes may be symptomatic of unexpected physics in classes of strongly correlated electron materials.

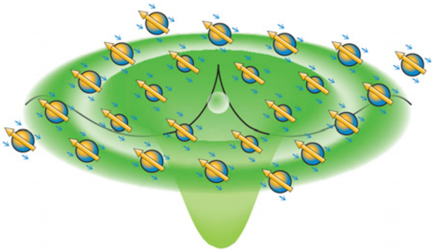

Fig. 1. Illustration of a Kondo-hole. At low temperatures, spins on itinerant electrons (small arrows) collectively compensate the spin (large arrow) on each U atom. The quantum process of spin compensation in this Kondo lattice produces a heavy-electron band structure that is homogeneous in space and characterized by a correspondingly uniform hybridization gap. Replacing a U atom by a nonmagnetic Th atom (white sphere) creates a Kondo-hole, where the hybridization is suppressed on the Th site and is modulated away from Th at a wavevector **Q**. The diameter of spheres centered on the large spins reflects the magnitude of the hybridization gap. At the Kondo-hole, an electronic bound state emerges with a state density that is peaked sharply but also modulated, as indicated by the solid curve.

In essential respects, URu_2Si_2 is typical of Kondo-lattice systems. Over a broad temperature range below room temperature, magnetic moments on the U atoms act as a dense collection of individual Kondo impurities. If this behavior were to persist at much lower temperatures, at which these STM experiments were performed, incoherent scattering of conduction electrons by each U Kondo impurity would produce a large electrical resistivity, much larger than that at room temperature. In contrast, the electrical resistivity of URu_2Si_2 and that of other Kondo-lattice materials at very low temperatures is hundreds of times smaller than at room temperature (3). The reason for this remarkable difference is that the periodic array of localized 5f electrons of U hybridize with light-mass itinerant electrons to create a new coherent electronic structure in which the original identity of the 5f electrons is lost as they become quantum mechanically entangled at low temperatures with the surrounding sea of itinerant charge carriers (6). The resulting heavy-electron band structure is characterized by a gap near the Fermi energy that is due to this hybridization, which is probed directly by tunneling spectroscopy. By scanning the tunneling tip over an exposed surface of U atoms in URu_2Si_2, Hamidian et al. (4) map the real-space dependence of the hybridization gap. When the scan does not include a Th atom, they find that the coherent heavy-electron band structure and associated hybridization gap develops, as expected, at low temperatures. However, when the tip scans an area including a Th impurity, these experiments show that the hybridization gap is suppressed on the impurity and that the magnitude of the gap is modulated away from the impurity with a wavevector **Q**, which is characteristic of the itinerant electrons before they have hybridized with the 5f electrons of U. Moreover, within the suppressed hybridization gap, a sharp peak in the electronic density of states emerges at the Th site, signaling an electronic bound state at the Kondo-hole. These results, illustrated in Fig. 1, are precisely those anticipated theoretically (5).

With 1% of the U atoms randomly replaced by Th, as in these experiments, the spacing between Th atoms is ≈2/|**Q**|, certainly close enough that waves of modulation in the magnitude of the hybridization gap from one Th site interfere with those radiating from neighbors—much like throwing a handful of pebbles on the surface of a calm pond. The combination of spatial randomness of the Kondo-holes and of the extended nature of their hybridization waves produces strong variations in the magnitude of the hybridization over the sample's surface, which is visualized in these experiments.

Being intrinsically a surface-sensitive measurement, these STM experiments leave open the question of whether the strong real-space heterogeneity of hybridization persists into the bulk of URu_2Si_2. Because a surface–vacuum interface breaks symmetry of the underlying bulk crystal structure, it is conceivable that the effect of a Kondo-hole on the surface

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does not reflect what happens under the surface. The compelling correspondence, however, between experimental observation (4) and a theoretical model (5), which is generically applicable to Kondo-holes in a bulk crystal, suggests that hybridization heterogeneity and the formation of an electronic bound state on the Kondo-hole seen at the surface persist in the bulk. In this case, an interpretation of the physics of Kondo-hole impurities in correlated electron matter is more complex than previously appreciated. Historically, real-space averaged measurements, such as electrical resistivity and specific heat measurements, on systems related to Th-doped URu_2Si_2 have been considered to be an electronic analog of Swiss cheese, with a Kondo-hole resonant state being embedded in an otherwise homogeneous background of uniformly hybridized heavy electrons (7). The picture emerging from the work of Hamidian et al. (4), however, is that the electronic “Swiss cheese” is highly textured, with the mass of heavy electrons being modulated on a length scale comparable to an interatomic spacing. This texture should be reflected in site-specific microscopic probes of the bulk electronic structure, such as NMR measurements, and will necessitate a reassessment of conclusions from previous studies of the consequences of a Kondo-hole.

A different but important issue, which will need to be addressed in the future, is the interplay between hybridization processes generating the heavy-electron band structure and the mysterious “hidden order” state that emerges in URu_2Si_2 at low temperatures (8, 9). The use of Kondo-holes as a probe of this mysterious state could be beneficial for revealing what is hidden.

Nanoscale electronic heterogeneity may be far more prevalent than often assumed.

A lesson from the work of Hamidian et al. (4) is that nanoscale electronic heterogeneity may be far more prevalent than often assumed and may have many unexpected consequences (10). Although the mechanism of heterogeneity induced by a Kondo-hole may be specific to nonmagnetic impurities in a Kondo lattice, scanning tunneling spectroscopy of the much-studied copper oxide high-temperature superconductors reveals real-space patches of electronic inhomogeneity (11), similar to what is seen in Th-doped URu_2Si_2. Like the Kondo lattice, electrons in the copper oxides also are strongly correlated, suggesting that electronic patchiness may be an intrinsic response of the correlated electron state to the inevitable presence of chemical heterogeneity. Depending on the spatial distribution of defects, it is possible that interference among waves of electronic heterogeneity could organize into new quantum states that are not anticipated from the physics of a uniformly correlated state, in effect creating order from disorder. Indeed, this possibility is suggested theoretically for a periodic array of Kondo-holes (5). Exploring experimentally and theoretically how electronic heterogeneity and possible new quantum states from it compete with energetically nearby broken symmetries, such as unconventional superconductivity, in strongly correlated materials is an exciting opportunity for future studies that will continue to challenge the physicist’s historical view of condensed matter and the role of impurity atoms.

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