Heavy Fermion Metals &
Superconductors

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Materials whose properties are governed by strong electronic correlations may exhibit fascinating phenomena ranging from colossal magnetoresistance to superconductivity and the fractional quantum Hall effect. Such materials are often of fundamental, sometimes also of technological interest. Unconventional superconductivity and quantum criticality in heavy fermion metals are among the most challenging phenomena. Detailed investigations are required for a more complete comprehension within this emerging field of condensed matter physics.

Heavy fermion metals

Heavy fermion metals typically contain 4f or 5f elements (e.g. Ce, Yb or U) and hence, local magnetic moments. In these materials, the ground state sensitively depends on the balance between two competing interactions, which are both determined by the strength of the hybridization between the localized 4f or 5f shells and the conduction electrons.

On the one hand, the Kondo entanglement results in a screening of these local spins resp. the associated local moments below a Kondo temperature TK, giving rise to a paramagnetic ground state. On the other hand, the indirect exchange coupling, the so-called RKKY interaction, can mediate long-range magnetic ordering. As the involved energy scales are small, varying an external control parameter like pressure, chemical composition or magnetic field may influence the hybridization such that the system’s ground state can be tuned between the magnetically ordered one and the paramagnetic Fermi liquid phase. Such a magnetic phase transition, that is not driven by thermal fluctuations but rather by quantum fluctuations (which are a consequence of the Heisenberg uncertainty principle), constitutes a Quantum Phase Transition which, if continuous, is called a Quantum Critical Point.

In the following we will argue that Fig. 2 represents a Si terminated surface. The most common defects in the structure of YbRh2Si2 should be an occupation of Si-sites by Rh, occupation of Rh-sites by Si, and Si vacancies. The line scans through the two observed types of defects clearly indicate that these defects cannot be caused by missing or additional atoms. Rather, the most numerous defects observed – the single protrusions – could originate from a larger Rh ion occupying a Si-site at the surface, i.e. the local Kondo entanglement, modifies the electronic structure of YbRh2Si2. The grey line indicates the surface electrons which are “bound” by the Kondo entanglement as well as the nature of the two types of defects encountered. An analysis of the position in energy of the three peaks marked by the arrows in Fig. 3 yields ~17 meV, ~27 meV and ~43 meV. These energies are in excellent agreement with those of the crystal electric field (CEF) excitations as observed by inelastic neutron scattering. This first (to the best of our knowledge) observation of CEF excitations by STS is of utmost importance as, on the one hand, it indicates that we truly measure bulk properties of our YbRh2Si2 samples and, on the other hand, it supports our conjecture of a Si terminated surface [4].

The hybridization of conduction and 4f electrons, i.e. the local Kondo entanglement, modifies the local density of states (DOS) p which determines the measured g(V,T). Loosely speaking, those conduction electrons which are “bound” by the Kondo entanglement reduce the number of electrons probed by
tunneling around zero bias voltage. We note that, in general, so called co-tunneling into the conduction band as well as into the heavy quasiparticle bands (resulting from the Kondo entanglement) is to be considered, but the latter is expected to be negligible here due to our focus on tunneling into Si terminated surfaces.

Our results [4] allow for important insight into the thermal evolution of the Kondo effect in YbRh$_2$Si$_2$. The observed zero-bias gap develops below $T_\text{f} \approx 30 \text{ K}$, only the lowest-lying CEF Kramers doublet is occupied. This allows for the development of a spatially coherent state which is manifested by an additional peak in $g(V)$ at $-6 \text{ mV}$ reflecting a “Kondo lattice resonance” related to an incomplete hybridization gap.

STS measurements at even lower temperatures ($T \geq 0.3 \text{ K}$) and in magnetic field are in progress in an effort to investigate the Fermi liquid properties and, hopefully, possible signatures of quantum criticality in this material.

Heavy fermion superconductors

In many of the heavy fermion metals, mostly those containing Ce, superconductivity is found experimentally. When such superconductivity was first discovered [5] it came unexpected as the Ce$^{3+}$ ions possess a local magnetic moment. In BCS superconductors, even small amounts of magnetic impurities suppress superconductivity since the local magnetic moment breaks the spin-singlet state of the Cooper pairs. This led to the speculation that the interaction mechanism in this class of heavy fermion superconductors could be magnetic in nature, i.e., the formation of Cooper pairs might not be mediated by phonons but rather by antiferromagnetic fluctuations. Nowadays it is widely believed that also superconductivity in the high-temperature cuprate superconductors is of such unconventional nature, detailed insight into the underlying mechanism is therefore highly desirable.

Therefore, we attempted STS on single crystals of CeCoIn$_5$, a known heavy fermion superconductor. Due to the low superconducting transition temperature of CeCoIn$_5$, $T_c \approx 2.3 \text{ K}$, we employed an Omicron manufactured cryogenic UHV STS with base temperature of $0.32 \text{ K}$ and magnetic field capabilities of up to $12 \text{ T}$. In order to prepare clean surfaces we cleaved the samples in situ. We regularly checked on the quality of the tunnel junctions by measuring the current dependence on tipsample distance, $I(z)$: Only junctions with work function $\Phi \geq 2 \text{ eV}$ were investigated further.

In Fig. 4, differential conductance, $g(V,T) = \frac{dI}{dV}$ spectra are presented as obtained for CeCoIn$_5$, within atomically flat terraces and for selected temperatures within the range $0.32 \text{ K} \leq T \leq 3 \text{ K}$. The curves were acquired at a bias voltage of $V = 14 \text{ mV}$ and a set-point current of $I_{\text{set}} = 340 \text{ pA}$. They are shifted vertically (except the one obtained at $T = 0.32 \text{ K}$) for clarity. We emphasize again that the $dI/dV$ curves are directly related to the electronic DOS of the sample. The superconducting gap around zero bias is clearly visible. Moreover, the observed conductance spectra of Fig.4 are nicely with the expected behavior of a d-wave superconductor (see [6] for more details). As also expected, upon increasing temperature the zero bias conductance increases, indicating a closing of the gap.

Most importantly, however, the gap does not disappear at $T_c = 2.3 \text{ K}$ (see red, solid markers in Fig. 4), but can still be recognized at $T = 3.0 \text{ K}$. Such a behavior, namely the development of a partial gap at temperatures above $T_c$ has been observed in the cuprate superconductors (termed “pseudogap”). Despite more than twenty years of intense research its origin, however, is still controversially discussed. With our investigations on the stoichiometric heavy fermion superconducting materials we hope to contribute to resolving this debate and gain further insight into the nature of unconventional superconductivity.

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The Research Group

Frank Steglich is Founding Director of the Max Planck Institute for Chemical Physics of Solids in Dresden, Germany. His research is devoted to strongly correlated electron systems, specifically to heavy fermion superconductivity and quantum criticality. He is also interested in highly disordered, magnetic and superconducting as well as thermoelectric materials.

Steffen Wirth also focusses his research on strong correlations particularly in intermetallics, manganites and chalcogenides, and with an emphasis on magnetotransport and STM investigations.

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References: