TT 98: Focus Session: Visualization of Heavy Fermion Formation through Scanning Tunneling Microscopy

Heavy fermion systems owe their name to a narrow band of heavy quasiparticles formed at the Fermi energy as a consequence of the Kondo effect and the consecutive lattice coherence of the Kondo quasiparticle states at low temperatures. The appearance of quantum coherence in the heavy fermion state as well as its instability and/or competition with magnetic ordering can give rise to a wealth of exotic phenomena, ranging from Kondo insulating behavior to quantum phase transitions, Fermi liquid breakdown and to superconductivity. The way how the quantum coherence emerges has been discussed controversially.

Recent progress in achieving low temperatures and sample preparation has established scanning tunneling microscopy (STM) and spectroscopy (STS) as an important new tool for detailed investigation of heavy fermion systems. As specific capabilities of STM, coherence can be probed by interference of different tunneling channels, and the magnetic coupling strength can be tuned by controling the geometry of model systems at metallic surfaces. The Focus Session will discuss these recent developments and prospects for understanding this enigmatic state of matter.

Organizers: Stefan Kirchner (Center for Correlated Matter, Hangzhou) and Johann Kroha (Uni Bonn)

Time: Thursday 15:00–18:15 Location: H 0104

Invited Talk TT 98.1 Thu 15:00 H 0104

Scanning Tunneling Spectroscopy: a New Tool for Probing Heavy Fermion Materials — •Piers Coleman — Department of Physics and Astronomy, Rutgers University, 136 Frelinghuysen Road, Piscataway, NJ 08854, USA — Department of Physics, Royal Holloway, University of London, Egham, Surrey TW20 0EX, UK

Over the past twenty years, the use of Scanning Tunneling Microscopy (STM) has emerged as a powerful tool for imaging the position dependent electronic excitation spectrum of correlated electron materials. More recently, this tool has been applied with great success to heavy electron metals, superconductors and Kondo insulators. Unlike one band materials, such as cuprate superconductors, STM into heavy fermion systems usually involves an interference between tunneling into the conduction d-band and the almost localized f-states, leading to Fano line-shape interference. I shall review the progress in this field, giving particular discussion of the insights gained into the hidden order in URu_2Si_2, the superconductivity in $CeCoIn_5$ and the topological Kondo insulator, SmB_6.

Topical Talk TT 98.2 Thu 15:30 H 0104

The Single-Atom Kondo Effect as a Local Probe for Magnetic Interactions — •Jörg Kröger — Institut für Physik, Technische Universität Ilmenau, 98693 Ilmenau, Germany

The Kondo effect of single magnetic atoms adsorbed to metal surfaces induces a zero-bias feature in spectra of the differential conductance acquired with a scanning tunnelling microscope. From the resonance line shape information on the interaction of the magnetic impurity with its local environment may be deduced. Embedding a single Co atom in artificially fabricated clusters of several Cu atoms leads to pronounced changes in the line shape of the Abrikosov-Suhl-Kondo resonance. Similar hybridization effects occur in single-atom junctions comprising non-magnetic as well as magnetic tips and a single Kondo atom. The distance-dependent magnetic interaction between two Co atoms has been explored in linear $CoCu_nCo$ clusters.

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Topical Talk TT 98.3 Thu 16:00 H 0104

Correlated Electrons under the Microscope: from Atomic Scale Model Systems to Bulk Materials — •Peter Wahl — SUPA, School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews, KY16 9SS, United Kingdom

The physics of strongly correlated and heavy fermion materials is often governed by a delicate balance between magnetic order and screening of magnetic moments. Therefore it is not surprising that some of the key features of the phase diagrams of these materials can be observed already in model systems consisting of two impurities or a chain of impurities. Specifically the two impurity Kondo problem has been theoretically shown to exhibit a quantum phase transition between an antiferromagnetic singlet state and a Kondo screened phase. I will show experiments by low temperature scanning tunnelling microscopy (STM) and spectroscopy for few impurities at surfaces which aim at mimicking these model systems, specifically a realization of the two-impurity Kondo model allowing for continuous tuning of the coupling between the two magnetic atoms by attaching one of the Kondo impurities to the tip of the STM. Attaching magnetic atoms from the surface to the tip of the STM is finally shown to allow for imaging of magnetic structure in strongly correlated electron systems at the atomic scale.

15 min. break.

Topical Talk TT 98.4 Thu 16:45 H 0104

Developing Kondo Lattice Coherence and Quantum Criticality in $YbRh_2Si_2$ — •Steffen Wirth[1], Silvia Seiro[1], Stefan Kirchner[2], Cornelius Krellner[3], Christoph Geibel[1], Qimiao Si[4], and Frank Steglich[1] — [1]MPI for Chemical Physics of Solids, Dresden, Germany — [2]MPI for Physics of Complex Systems, Dresden, Germany — [3]Goethe University Frankfurt, Germany — [4]Rice University, Houston, Texas, USA

Hybridization is a fundamental concept in strongly correlated electron physics. In heavy fermion metals, it may result in the generation of low-energy scales that can give rise to quantum criticality and unconventional superconductivity. An important techniques that helped shaping our understanding of nonlocal correlations – magnetic and superconducting – has been tunneling spectroscopy (STS) with its unique ability to give local, microscopic information that directly relates to the one-particle Green's function. We investigated $YbRh_2Si_2$, an archetypal heavy fermion metal. Quantum criticality is discussed in terms of an antiferromagnetic instability and a Kondo break-down of the heavy quasiparticles. STS studies identified a hybridization-induced gap-like feature of the tunneling conductance. Here we focus on the evolution of the Kondo lattice. While the Kondo lattice starts forming already at the single-ion Kondo temperature, lattice Kondo effects dominate only at much lower temperatures. This establishes a hierarchy of energy scales. Finite-temperature signatures of the QCP are observed in field-dependent STS. Our findings are augmented by band structure calculations and transport measurements.

Invited Talk TT 98.5 Thu 17:15 H 0104

Visualizing the Formation and Magnetically-Mediated Cooper Pairing of Heavy Fermions — •JC Seamus Davis — Cornell University, Ithaca, NY 14850, USA

We recently introduced spectroscopic imaging STM to the study of heavy fermions and achieved the first heavy-quasiparticle interference imaging and direct observation of splitting of a light k-space band into two new heavy fermion bands due to the hybridization process (Nature **465**, 570 (2010)). Key specifics of the Cooper pairing mechanism are encrypted in the k-space structure of the superconducting energy gaps $\Delta_{\alpha,\beta}(k)$ on the heavy bands $E(k)_{\alpha,\beta}$. With energy scales for both these effects so low (sub meV), it was impossible to directly measure $\Delta(k)$ for any heavy-fermion superconductor. We introduced Bogoliubov quasiparticle interference (QPI) imaging using milli-Kelvin STM for $CeCoIn_5$. The heavy band structure $E(k)_{\alpha,\beta}$, the Fermi surface, plus the superconducting $\Delta_{\alpha,\beta}(k)$ structure were measured directly for the first time (Nature Physics **9**, 458 (2013)). Novel SI-STM techniques to measure the k-space structure of the f-electron magnetic interactions were introduced for $CeCoIn_5$. Solving the superconducting gap equations on the measured $E(k)_{\alpha,\beta}$ with the hypothesis that these magnetic interactions mediate the Cooper pairing, reveals succession of quantitative predictions about the superconducting state. We established excellent quantitative agreement between these diverse predictions and many measured characteristics of $CeCoIn_5$. This provides the first direct evidence that its heavy fermion Cooper pairing is mediated by the f-electron magnetism. (PNAS **111**, 11663 (2014))

TT 98.6 Thu 17:45 H 0104

Single-Co Kondo effect on Au(110) — •Stefan Meierott, Nicolas Néel, and Jörg Kröger — Institut für Physik, Technische Universität Ilmenau, D-98693 Ilmenau, Germany

Scanning tunneling spectra of the differential conductance acquired atop single Co atoms on Au(110) exhibit a zero-bias resonance. This feature is attributed to the spectroscopic signature of the Kondo effect. Spatially resolved spectroscopy unveils a mismatch between the maximum resonance amplitude and the Co center. Based on currently available theory [1] the experimental observations are reproduced by taking the adsorption of Co on the facet of a Au(110) missing row into account.

Financial support by the Deutsche Forschungsgemeinschaft through KR 2912/7-1 is acknowledged.

[1] M. Plihal et. al., Phys. Rev. B 63, 085404 (2001)

TT 98.7 Thu 18:00 H 0104

Scanning tunneling spectroscopy and surface quasiparticle interference in models for the topological Kondo insulator SmB_6 — •Pier Paolo Baruselli and Matthias Vojta — Institut für Theoretische Physik, Technische Universität Dresden, 01062 Dresden, Germany

SmB_6 is one of the candidate compounds for topological Kondo insulators, a class of materials which combines a non-trivial topological band structure with strong electronic correlations. We present a theoretical study [1] of the surface-state signatures induced by dilute impurities in scanning tunneling spectroscopy and quasiparticle interference. We employ a multiband tight-binding description, supplemented by a slave-particle approach to account for strong interactions. We discuss the spin structure of the three surface Dirac cones and provide concrete predictions for the energy and momentum dependence of the resulting QPI signal. Moreover, we analyse the effect of a 2x1 surface reconstruction on such signals.

[1] P. P. Baruselli and M. Vojta, PRB 90, 201106(R) (2014)