Visualizing Heavy Fermions and their Cooper Pairing

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9. Summary and Conclusions

Heavy fermion materials are strongly correlated electronic systems whose complex phase diagram is characterized by the competition between Kondo screening and antiferromagnetic ordering. Tuning this competition via temperature, magnetic field, or doping, allows for the emergence of a plethora of exciting phenomena ranging from unconventional superconductivity to non-Fermi liquid behavior and quantum criticality. However, the set of interactions that give rise to the rich heavy fermion phase diagram also makes both empirical and rigorous theoretical descriptions extremely difficult.

The recent development of millikelvin spectroscopic imaging scanning tunneling microscopy (SI-STM) for use in the long established field of heavy fermion physics has introduced the unique capability of having simultaneous access to both real space and momentum space electronic structure information. The novel insight provided has in turn provided theorists with an unprecedented avenue to develop and test new theoretical tools, furthering the understanding and interpretation of SI-STM data while also providing a whole new class of predictions.

The review will describe the rapid development of both the experimental methods of SI-STM and its theoretical formalism to address fundamental aspects of heavy fermions physics. The organization of this article naturally reflects the symbiotic evolution of the two facets in that almost every experimental discovery is complemented by a theoretical advance and vice versa. After reviewing the fundamental aspects of heavy fermion physics from the Kondo lattice to $f$-electron superconductivity, the basic principles of SI-STM measurements will be introduced. The following section focuses on real space measurements of differential conductance spectra on different termination surfaces of various heavy fermion compounds. The difference in the shape of the spectra is shown to arise from a complex multi-channel tunneling process that is characterized by quantum interference between quasi-localized $f$-electron states and delocalized conduction states. Subsequently, complementary momentum space methods introduce heavy fermion quasiparticle interference imaging (HF-QPI) and the theoretical machinery to utilize the Fourier transform images
from SI-STM to calculate momentum space electronic structure. This method yielded the first direct observation of heavy fermion formation.

While defects in heavy fermions have been studied for decades it was only recently with the advent of Kondo-Bogoliubov-de-Gennes theory that local changes to the real space heavy fermion electronic structure could be calculated. They predicted characteristic real space oscillations in the strength of the Kondo screening, the hybridization. These hybridization oscillations represent a class of electronic structure modulation that only SI-STM has been able to detect. Furthermore, when applied to a dilute concentration of defects both the calculation and data showed intense disordering of the electronic structure which resolved bulk probe observations from a microscopic perspective.

The final section addresses the recent experimental and theoretical advances in measuring the superconducting energy gap structure and in identifying the superconducting paring symmetry and mechanism in the heavy fermion superconductor CeCoIn$_5$. The realization of Bogoliubov quasi-particle interference (BQPI) spectroscopy in the superconducting state in conjunction with its theoretical description has permitted the direct identification of the $d_{x^2-y^2}$-symmetry and complex momentum structure of the superconducting gap. Moreover, by using newly gained insight into the relation between magnetic interactions and the momentum structure of the heavy bands, the effective superconducting pairing interaction can be identified. This, in turn allowed one to compute not only the superconducting pairing symmetry and the critical temperature, but also a series of superconducting properties of CeCoIn$_5$, such as the BQPI and phase-sensitive QPI spectra, the spin-lattice relaxation rate as well as the energy position and shape of the magnetic resonance mode. The good agreement of these theoretical results with the experimental findings present very strong and direct evidence for a magnetic $f$-electron mediated superconducting pairing mechanism in CeCoIn$_5$. 