8 Unconventional Superconductivity: Overview and Planar Tunneling into a Kondo Lattice

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1 Overview

Unconventional superconductors differ from conventional superconductors in that they typically exhibit a ubiquitous phase diagram with intriguing, correlated electron phases that break the symmetry of the underlying lattice at temperatures well above T_c. These non-Fermi liquid phases remain some of the greatest unsolved problems in physics. After this overview, I will present some of our recent work on planar tunneling into Kondo insulators, and a possible new paring mechanism in the heavy-fermion superconductor $CeCoIn_5$.

2 Introduction

The past several years, I have been giving colloquia and public lectures with the title "The Dark Energy of Quantum Materials." Why this title? One reason is that we all were enthralled with the LIGO successful of detection of gravity waves – measuring a motion of less than the width of a proton, and astoundingly, for a power of $3.6{\cdot}10^{49}$ Watts, which is more than the combined power of all light radiated by all the stars in the observable universe. That LIGO detected gravity waves signified that for the first time, we could look at the universe in a new way, without using light or matter.

The LIGO observatory was invented to find gravity waves, as it did, but the larger question is: Will this new observatory help us to understand dark matter or other phenomena we have not previously been able to explain. In quantum materials, there is not a single phenomenon to explain but a host of correlated electron states. We in condensed matter have developed a wide host of observatories, i.e., measurement techniques (e.g., ARPES, STM, EXAFS, ...); have significantly improved our crystal growth techniques; and have developed a host of computational techniques. All of these new and improved observatories: measurement, growth, and computational techniques are addressing correlated electrons with more and more success. The larger question here is: Will these hosts of quantum matter observatories help us to understand the many non-Fermi liquid phases. In the longer term, can we learn to predictively design correlated functional materials such as superconductors and thermoelectrics?

My many years in studying superconductivity have led me to adopt a general overview that understanding unconventional superconductivity is no less fundamental than cosmology, and no less fascinating, with one important complication: There are many families of unconventional superconductors, and thus, many fundamental questions to be addressed, making this a multi-modal complex problem. Here, I give my personal overview of the fundamental questions, with the apology that I will not have all the scholarship in time for this publication.

The BCS electron-phonon coupled theory of conventional superconductivity is considered by most to be one of the few solved problems in quantum materials. Conventional superconductivity is typically characterized by materials that exhibit Fermi liquid behavior above T_c, while below T_c, the superconducting order parameter is of the same symmetry as the underlying lattice. This contrasts with unconventional superconductivity, which often reveals non-Fermi liquid (NFL) behavior above T_c, and where the T_c as a function of some variable such as pressure or doping, varies as a dome across that phase diagram. Unconventional superconductivity was discovered in 1979 by Steglich and co-workers in heavy Fermions [1], and in 2001, Lonzarich and co-workers discovered the first domed phase diagram in a heavy fermion superconductor as a function of applied pressure in $CePd_2Si_2$ [2]. At the time, it was surprising that superconductivity could appear associated with a magnetic state, and the electron-phonon theory of Cooper pairing was questioned. Since then, many families of unconventional superconductors have been discovered that exhibit a domed phase diagram, typically with NFL at temperatures above the dome.

We can describe the electronic properties of Fermi liquids with general electronic structure calculations: Simply put, the electronic, thermodynamic, and optical properties are explained by the lattice structure and the atoms that make up the lattice. We are also able to describe the electronic, thermodynamic, and optical properties of the superconducting state, both conventional and unconventional, because, as to date, all superconductors we know of are composed of Cooper pairs, so can be described with the Bogoliubov-de Gennes equations. Conventional metallic superconductors are easy to model, and there is more of a challenge in unconventional superconductors where you need to take the symmetry of the superconducting order parameter and the possibility of more than one band in to account. So even if you do not know the microscopic mechanism of the Cooper pairing, the superconducting state can be modeled.

The larger question is that the NFL states above the dome typically cannot be described by simple Fermi liquid theory due to electron-electron correlations. And these correlations are quite varied: In the heavy fermions the electronic mass measured thermodynamically is larger than can be described by Fermi liquid theory; in the cuprates there is the enigmatic pseudogap where electronic stripes can be found; in the di-chalcogenides the T-dependent charge-density wave behavior cannot be accounted for [3]; there are quantum-critical fluctuations above quantum critical points; and in the Fe-based superconductors there exists electronic nematic phases where the electrons can form elongated clusters even at temperatures in the tetragonal phase. Before the discovery of the Fe-based superconductors, unconventional superconductivity was defined as having a superconducting order parameter of a lower symmetry than the underlying lattice. Since the proposed symmetry of their superconducting state, $s_{\pm}$, is of the same symmetry as the underlying lattice, a more general and accurate definition is that the symmetry of the electron fluid above the dome breaks the symmetry of the underlying lattice – most clearly demonstrated in the nematic phase of the Fe-based superconductors.

3 Planar Tunneling

The work in my laboratory primarily involves electron transport, with a focus on planar tunneling spectroscopy (PTS). In this technique, electrons are injected from one electrode to another across a thin, insulating barrier. It was PTS that showed phonons were responsible for the Cooper pairing: that the Pb phonons that were observed by neutron scattering, were observed in the Pb tunneling density of states [4].

In normal-insulating-normal (NIN) junctions, single-step elastic tunneling will reveal Ohm's law because in the tunneling equation, the conductance is calculated from the energy integral over the Fermi velocity times the density of states, which divide out for Fermi liquids, as dictated by Harrison's theorem [5]. This theorem was derived for one-dimensional elastic tunneling between simple metals. If one of the electrodes is replaced with a superconductor (S), the SIS tunneling conductance reveals the quasiparticle superconducting density of states, including the energy gap and the coherence peaks at the gap edge, precisely because a superconductor is not a Fermi liquid. In fact, planar tunneling, with the proper diagnostics, is a direct probe of NFL behavior. The same arguments can be made for point contact spectroscopy. Some of our examples include mapping out the nematic phases in several families of Fe-based superconductors [6] and detecting the hybridization gap as a Fano line shape in background conductance of the heavy fermion $CeCoIn_5$ [7].

In planar tunneling spectroscopy, diagnostics are required to determine the quality of the junctions, in particular, to see if the predominant transport across the junction is single-step elastic tunneling. In studying new materials, it is important to start with a well-known superconductor as the counter-electrode, such a Pb (which is also easy to grow) to determine the quality of the junction from the quality of the measured Pb tunneling density of states. Then you can easily drive the Pb normal ($H_c \sim 0.1$ T; $T_c \sim 7.2$ K) so the Pb becomes a Fermi liquid and the resulting non-ohmic conductance arises from any NFL behavior of the new material. Another important diagnostic is reproducibility: Once the growth of the planar junction is worked out (includes growing or polishing one electrode, growing or forming a thin insulating tunnel barrier, then depositing the counter-electrode) the PTS conductance must be of good quality and reproducible. After experience with the new material is acquired, non-superconducting counter-electrodes can be used because the quality of the now-known, reproducible, tunneling density of states of the new material becomes an important diagnostic.

4 Planar Tunneling into the Heavy Fermion $CeCoIn_5$

In the case of PTS into $CeCoIn_5$, we created reproducible, high-quality planar tunnel junctions on three major crystallographic orientations: [001], [100], and [110] [8]. As described in general, above, using Pb counter electrodes, we establish the quality of the junctions from the measured Pb tunneling density of states at low temperature and zero applied magnetic field, where the expected Pb superconducting gap and coherence peaks are clearly observed. Once the junction quality is established, the Pb is driven normal with the applied field of 0.2 T, and since the H_{c_2} of $CeCoIn_5$ is 4.95 T for [001] and 11.8 T for [100] and [110] that applied field is a tiny perturbation. Our earlier work on $CeCoIn_5$ showed that the superconducting order parameter symmetry was $d_{x^2-y^2}$ [7], which has been verified since. Our PTS verified that symmetry, and that there were preformed pairs above T_c [9, 10].

The compelling findings are these. First, at temperatures below T_c (2.3 K), with applied magnetic field, the $CeCoIn_5$ tunneling density of state for [001] and [100] shows a suppression of the d-wave gap with increasing field, as expected, and surprisingly, this gap evolves slowly into a splitting, or field-induced gap, that grows linearly with applied field up to the highest fields

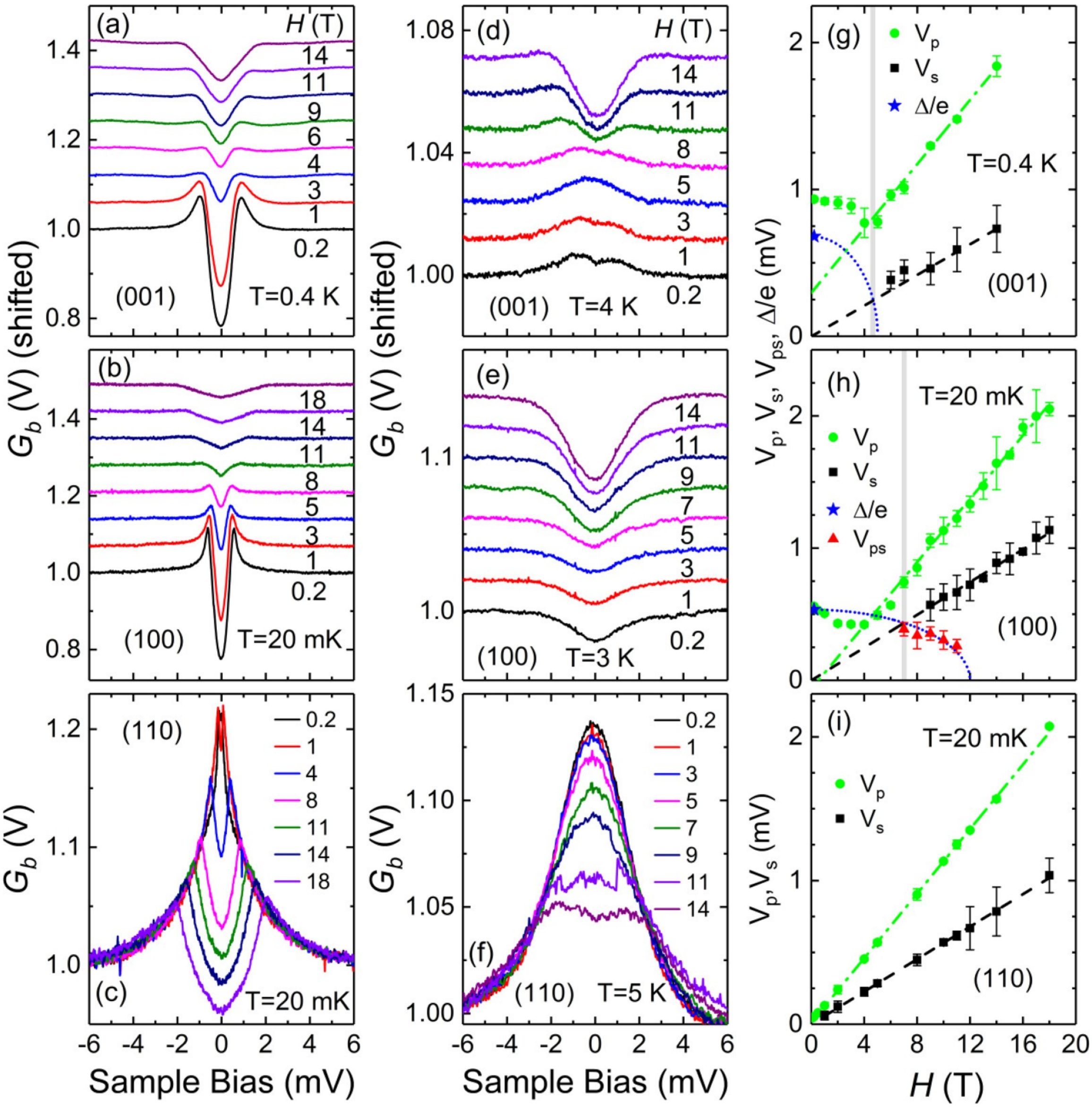

Fig. 1: *Magnetic evolution of the planar tunneling conductance for CeCoIn$_5$ in the [001] (top), [100] (middle), and [110] (bottom) orientations for $T < T_c$. The first column shows the conductance for $T < T_c = 1.3$ K and the center column in the temperature range of the preformed pairs (T = 3–5 K), where curves are shifted vertically for the [001] and [100] orientations. The right column plots the magnetic evolution of the superconducting gap and the field splitting at low temperature. Note the superconducting gap evolves into a splitting well above H_{c_2}. Not shown here, at higher temperatures (> 10 K), there is no observable superconducting gap feature, as expected, and no subsequent field dependence (after [8]).*

measured (18 T). The same behavior occurs in the temperature regime between T_c and that of the preformed pairs (∼5 K), a gap is seen that evolves into a high-field splitting. At temperatures above that of the pre-formed pairs, there is almost no field dependence.

We find that the high field splitting *only* appears when there are Cooper pairs, or preformed pairs. We note that the 40 meV spin-correlation resonance observed by inelastic neutron scattering (INS) is seen in the tunneling in the cuprate and Fe-based superconductors but is not seen in CeCoIn$_5$ tunneling. In INS, there is a 0.6 meV resonance, but it is robust to doping [11] and this feature is not seen in tunneling spectroscopy. We conclude then that the spin-spin correlations that play a role in the pairing of the high-Tc superconductors do not play a role in $CeCoIn_5$. Instead, this heavy-Fermion material has f-level magnetic scattering. Therefore, in comparison with the planar tunneling models of Anderson and Applebaum, where the tunneling conductance exhibits a linear splitting with applied magnetic field due to Kondo scattering by magnetic impurities in the tunneling barrier [12], we surmise that the pairing in $CeCoIn_5$ may arise, at least in part, from f-level scattering.

5 Conclusion

In conclusion, unconventional superconductivity is a complex subject with many important problems to be solved. It is clear to me that there is not only one solution for the pairing mechanism in all superconductors [13], which makes these problems daunting. Just as the new LIGO observatories have promise for understanding fundamental questions of our cosmological makeup, I believe that our myriad or new and novel measurement, growth, and computation techniques will help us understand the many questions of non-Fermi liquid behavior and unconventional superconductivity.

References

[1] F. Steglich, J. Aarts, C.D. Bredl, W. Lieke, D. Meschede, W. Franz, and H. Schäfer, Phys. Rev. Lett. **43**, 1892 (1979)

[2] F.M. Grosche, I.R. Walker, S.R. Julian, N.D. Mathur, D.M. Freye, M.J. Steiner, and G.G. Lonzarich, J. Phys.: Condens. Matter **13** 2845 (2001)

[3] E. Morosan, H.W. Zandbergen, B.S. Dennis, J.W.G. Bos, Y. Onose, T. Klimczuk, A.P. Ramirez, N.P. Ong, and R.J. Cava, Nat. Phys. **2**, 544 (2006)

[4] W.L. McMillan and J.M. Rowell, Phys. Rev Lett **14**, 108 (1964)

[5] W.A. Harrison, Phys. Rev. **123**, 85 (1961)

[6] H.Z. Arham, C.R. Hunt, W.K. Park, J. Gillett, S.D. Das, S.E. Sebastian, Z. J. Xu, J.S. Wen, Z.W. Lin, Q. Li, G. Gu, A. Thaler, S. Ran, S. L. Bud'ko, P.C. Canfield, D. Y. Chung, M.G. Kanatzidis, and L.H. Greene, Phys. Rev. B **85**, 214515 (2012)

[7] W.K. Park, J.L. Sarrao, J.D. Thompson, and L.H. Greene, Phys. Rev. Lett. **100**, 177001 (2008)

[8] K. Shrestha, S. Zhang, L.H. Greene, Y. Lai, R.E. Baumbach, K. Sasmal, M.B. Maple, and W.K. Park, Phys. Rev. B **103**, 224515 (2021)

[9] S. Ernst, S. Wirth, F. Steglich, Z. Fisk, J.L. Sarrao, and J.D. Thomson, Phys. Stat. Sol. B **247**, 624 (2010)

[10] Y. Fasano, P. Szabo, J. Kacmarcik, Z. Pribulova, P. Pedrazzini, P. Samuely, and V.F. Correa, Physica B **536**, 798 (2018)

[11] Y. Song, J. Van Dyke, I.K. Lum, B.D. White, S. Jang, D. Yazici, L. Shu, A. Schneidewind, P. Čermák, Y. Qiu, M.B. Maple, D.K. Morr, and P. Dai, Nat. Commun. **7**, 12774 (2016)

[12] L.Y.L. Shen and J.M. Rowell, Phys. Rev. **165**, 566 (1968);
P.W. Anderson Phys. Rev. Lett. **17**, 95 (1966);
J. Applebaum Phys. Rev. Lett. **17**, 91 (1966)

[13] J. Levallois, M.K. Tran, D. Pouliot, C. N. Presura, L.H. Greene, J. Eckstein, J. Uccelli, E. Giannini, G.D. Gu, A.J. Leggett, and D. van der Marel, Phys. Rev. X **6**, 031027 (2016)