Abstract

The structures, the phase diagrams, and the appearance of a neutron resonance in the superconducting state provide phenomenological evidence which relate the heavy fermion, cuprate and Fe superconductors. Single- and multi-band Hubbard models have been found to describe a number of the observed properties of these materials so that it is reasonable to examine the origin of the pairing interaction in these models. Here based on the experimental phenomenology and studies of the momentum and frequency dependence of the pairing interaction for Hubbard-like models, we suggest that spin-fluctuation mediated pairing is the common thread linking this broad class of superconducting materials.

For a number of years there have been suggestions that just as the electro-phonon interaction leads to pairing in a variety of non-magnetic superconducting materials, pairing mediated by the exchange of spin-fluctuations is responsible for the superconducting seen in a wide class of nearly antiferromagnetic materials. These suggestions have ranged from proposals that spin-fluctuations near an antiferromagnetic instability were responsible for pairing in some organic BEDT salts and heavy fermion systems [1, 2] to later work that included the cuprate [3, 4, 5] as well as the recently discovered Fe superconductors [6, 7, 8]. One could also include Sr$_2$RuO$_4$ in this class of unconventional superconductors [9], where in this case ferromagnetic...
spin-fluctuations are important. Here we will focus on the heavy fermion, cuprate and Fe superconductors. We first argue that their chemical and structural makeup, their phase diagrams and evidence of quantum critical behavior, along with the observation of a neutron scattering spin resonance in the superconducting phase support the notion that they form a related class of superconducting materials. We then note that a number of their observed properties are described by Hubbard-like models and that calculations show that the pairing in such models arises from the exchange of spin fluctuations. We conclude that pairing arising from the exchange of spin-fluctuations near an antiferromagnetic instability is the common thread linking the heavy fermion, cuprate and Fe superconductors[10].

To begin with, these materials are all known to occur in families. For example, one has the 115 heavy fermion family CeTIn$_5$ with T=Co, Rh and Ir, and the actinide 115 PuTGa$_5$ with T=Co and Rh. For the cuprates, one has the well-known Hg, Tl and Bi families and similarly for the Fe superconductors there are a number of different families including the (1111) LaOFeAs, the 122 Ba(FeAs)$_2$ and the (11) Fe(Se$_{1-x}$Te$_x$) groups.

Structurally, these materials are layered quasi-2D systems with a square planar arrangement of ions containing hybridized d or f orbitals which have local magnetic character and lay near the Fermi energy. In the heavy fermion materials, the f-electrons hybridize with the spd electrons and the parent compound is a low temperature, coherent, heavy mass, paramagnetic metal. Pressure or doping can alter the delicate balance between antiferromagnetism and superconductivity. In the cuprates, the Cu 3d electrons hybridize with O p-orbitals and the parent compound is a charge-transfer antiferromagnetic Mott insulator which becomes superconducting when doped. In the Fe-pnictide and chalcogen families, the Fe 3d orbitals hybridize through As or Se (Te) 4p orbitals and the parent compound is a semi-metallic antiferromagnet. In this case, pressure, chemical pressure or doping can lead to superconductivity.

The phase diagrams of these materials typically exhibit antiferromagnetism near or in some cases coexisting with superconductivity. Furthermore, via doping, chemical pressure or hydrostatic pressure one can move from the antiferromagnetic to the superconducting phase. In addition, there can also occur nematic as well as striped magnetic and charge density wave phases. In some cases, such as the underdoped cuprates, one is near a charge-transfer antiferromagnetic Mott phase. However, the common element seen in the various phase diagrams of the heavy-fermion [11, 12, 13], cuprate [14, 15]
and Fe \[16, 17\] families is the proximity of the antiferromagnetic and superconducting regions.

Another common feature is evidence for the occurrence of a quantum critical point (or points), veiled by the superconducting dome, which gives rise to characteristic power law temperature dependencies at temperatures above \(T_c\) \[18, 19, 20, 21\]. Along with this, there can be coexistence of magnetic and superconducting order and electronic structure reconstruction due to the presence of the magnetic order \[22, 23, 24\]. In all three classes of materials there is evidence of a sensitivity of the superconducting pairing to the structure of the Fermi surface or surfaces.

In these materials, the ratio of the superconducting transition temperature \(T_c\) to the Fermi energy or coherence scale is similar and large relative to that of the traditional electron-phonon superconductors \[4\]. Furthermore, electronic structure frozen phonon calculations of the electron-phonon pairing strength find that it is far too weak to give the observed superconducting transition temperatures of these systems \[25, 26\].

Finally, a key experimental observation linking these materials is the appearance of a neutron scattering magnetic resonance in the superconducting state at an antiferromagnetic or SDW wave vector \(Q\). This type of resonance, first observed in YBCO by Rossat-Mignod \[27\], has now been seen in the heavy-fermion \[28\], cuprate \[29, 30\] and Fe \[31, 32\] superconductors. It implies that the gap changes sign between regions on the Fermi surface (or surfaces) separated by momentum \(Q\), which contribute significantly to the spin scattering \[33, 34\]

\[
\Delta(k + Q) = -\Delta(k). \tag{1}
\]

Thus, all of these materials have an “unconventional” gap with a magnetic resonance at an energy which scales with the gap \[35\]. In addition, the magnitude of the gap typically rises rapidly as the temperature decreases below \(T_c\) and reaches a \(2\Delta_0/kT_c\) value which is larger than the expected BCS value. This behavior is consistent with a picture in which not only are the same electrons involved with both the magnetic and superconducting properties, but the same electrons that are pairing participate in the pairing interaction \[33, 36\].

From a theoretical perspective, the single- and multi-band Hubbard models provide a framework for describing these materials \[37, 38\]. While a multi-band Hubbard model is needed to describe the charge-transfer aspect of the cuprates and 5-band models are presently used for the Fe-superconductors, a
substantial part of the basic underlying physics is believed to be captured in the single-band Hubbard model. For example, this basic model at half-filling is known to exhibit an antiferromagnetic Mott insulating state, while the doped system exhibits stripes and d-wave pairfield correlations [39]. There are also numerical calculations which show that there is a magnetic resonance peak present in the superconducting state [40].

Calculations of the irreducible particle-particle pairing interaction for the single band Hubbard model show that it is associated with the particle-hole \( S = 1 \) exchange channel, i.e., spin-fluctuations [41]. In particular, recent calculations show that the dynamics of the pairing interaction reflect the structure in the imaginary part of the dynamic spin susceptibility [42]. There have also been a number of RPA [4, 5] and weak coupling renormalization group treatments [43, 44] of 5-band Hubbard models for Fe which conclude that spin-fluctuations provide the pairing interaction in the Fe-pnictides and chalcogen superconductors.

Beyond the pairing interaction, which we take to be the irreducible 4-point vertex in the zero center of mass momentum and energy particle-particle channel, there are a number of other factors which influence the onset of superconductivity. There is of course the structure of the single particle propagator. Near a Mott-antiferromagnetic transition, the superconducting transition temperature is suppressed by the Mott gap which opens in the single particle spectrum even though the 4-point vertex pairing interaction is strong. There is the interplay of competing orders, the role of nematic and stripe-like fluctuations [45] and the possible reconstruction or fluctuation of the Fermi surface [46, 47]. There is also the interesting possibility that an optimally inhomogenous structure may lead to an enhanced \( T_c \) [48]. Nevertheless, from calculations carried out on clusters with inhomogeneities it appears that the short range spin-fluctuations mediate the pairing interaction [49].

In summary, there are similar material, experimental and theoretical features relating the heavy fermion, cuprate and Fe superconductors. The materials come in families which contain quasi-2D layers of correlated d or f electrons. Their temperature-doping and magnetic field phase diagrams show antiferromagnetism in close proximity to superconductivity. The resonant peak observed in inelastic neutron scattering experiments in the superconducting phase provide a signature for an unconventional gap \( \Delta(k + Q) = -\Delta(k) \). This resonance also implies that the same electrons are involved in both the magnetism and the superconductivity. The rapid onset of the gap as the
temperature is lowered below $T_c$ as well as the large $2\Delta_0/kT_c$ ratio further suggest that these electrons are also involved in the effective pairing interaction.

Single- and multi-band Hubbard models exhibit a number of the properties seen in these materials. Numerical studies of the effective pairing interaction in the single-band Hubbard model and various weak coupling calculations on multi-band models find unconventional pairing mediated by an $S=1$ particle-hole channel. Thus while the heavy fermion, cuprate and Fe-pnictide (or chalcogen) materials exhibit a wide range of properties, we believe that spin-fluctuated mediated pairing provides the common thread which is responsible for superconductivity in all of these materials.

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