Interband pairing and superconductivity of heavy-fermion systems

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The superconductivity of systems with heavy fermions is explained in a model of singlet interband pairing of the type $\langle a^{+}_{f\uparrow} a^{+}_{d\downarrow} - a^{+}_{f\downarrow} a^{+}_{d\uparrow} \rangle$. This model gives a qualitatively reasonable description of the basic experimental properties of these systems.

Superconductors with heavy fermions,[1,2] i.e., compounds of rare-earth metals and actinides, in which there are electrons with huge effective masses $m_f \sim (10^2\text{–}10^3) m_0$ at the Fermi surface at low temperatures, have recently attracted considerable interest. The nature of the heavy fermions and that of the superconductivity in these compounds have yet to be finally resolved. There have been suggestions that the pairing in these compounds is anisotropic and possibly a triplet pairing, by analogy with ^{3}He. On the other hand, there are arguments in favor of a more ordinary singlet superconductivity, especially in the first superconductor of this class,[2,3] $CeCu_2Si_2$.

Discussions of the superconductivity of these systems have usually focused on the pairing of heavy "f-electrons." However, there are strong arguments that these systems contain, in addition to heavy electrons, light "d-electrons" with $m_d \cong m_0$. Direct experimental evidence for this position has emerged from a study of the de Haas–van Alphen effect.[4] We are naturally led to ask what relative roles these two components play in the superconductivity. It is clear from the experimental data, in particular, from the jump in the heat capacity, $\Delta C / \gamma T_c$, and from the value $\partial H_{c_2} / \partial T$, that a heavy component is participating in the pairing.[1,2] On the other hand, the London penetration depth, ordinarily taken from the expression $\lambda_L^2 = mc^2 / 4\pi n_s e^2$, turns out in this case to be on the same order of magnitude as in ordinary superconductors.[2] This result can be attributed to a screening of the field by light carriers. There are also indications that some of the electrons (heavy electrons in UPt_3 and light electrons in

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$CeCu_2Si_2$) remain normal down to temperatures $T \ll T_c$ (Ref. 3); this conclusion follows from the behavior of the heat capacity $C_s(T)$ and that of the thermal conductivity $K_s(T)$ at $T < T_c$.

In this letter we consider only one of the various possible ways to qualitatively explain the basic results observed experimentally on superconductivity in heavy fermion compounds. Specifically, we assume that in these systems, which we treat phenomenologically as two-component systems, there can be a *singlet pairing of electrons from different bands* of the type $\langle a^+_{f\uparrow} a^+_{d\downarrow} - a^+_{f\downarrow} a^+_{d\uparrow} \rangle$. This possibility was examined a rather long time ago in Refs. 5 and 6. It was discussed in Refs. 8 and 9 in connection with heavy-fermion systems. (We learned of the last of these papers after we have already obtained our basic results.)

We begin by noting that a tendency toward an interband singlet pairing of this type can be seen even in the simple model of an Anderson lattice or a Kondo lattice, widely used today to analyze the properties of heavy-fermion systems. In these models, a Kondo interaction.

$$H_{int} = \frac{J}{4} a^+_{fs} \vec{\sigma} a_{fs'} a^+_{d\sigma} \vec{\sigma} a_{d\sigma'} - \frac{J}{4} n_d n_f \tag{1}$$

arises in a natural way and leads, in particular, to the possibility that a singlet pair of *f*- and *d*-electrons will form. Although the situation is more complex in reality, it is useful as a first step to analyze the possible consequences of an interband pairing of this sort in the simplest approximation, analogous to the BCS approximation.

For simplicity, we correspondingly assume that the Fermi surfaces for the *f*- and *d*-bands, with the dispersion $\epsilon_f(\mathbf{p}) = p^2/2m_f - \mu_f$, $\epsilon_d(\mathbf{p}) = p^2/2m_d - \mu_d$, coincide. We also assume that the coupling is weak (i.e., we assume $T_c \ll W_{f,d}$, where $W_f \cong p_F^2/2m_f$ and $W_d \cong p_F^2/2m_d$ are the widths of the bands—natural cutoff parameters in this model). In the case we can easily derive an expression for the critical temperature T_c (cf. Ref. 9):

$$T_c \cong \sqrt{W_f W_d}\, e^{-\frac{1}{N_d(0) J}}, \tag{2}$$

where $N_d(0) \sim 1/W_d$ is the state density in the wide *d*-band.

In this case, however, there is no reason to expect $T_c \ll W_f$. In particular, in a model of the Kondo-lattice type, with $W_f \sim T_K$, the conditions $T_c \sim T_K$ would be more likely. If we consider the opposite limit, $T_c \gtrsim W_f$, we conclude that all the electrons of the narrow *f*-band, not exclusively those related by the condition $(\mathbf{k}, -\mathbf{k})$, can participate in the pairing. One can show that in this case we actually have the following expression for T_c:

$$T_c \cong W_d\, e^{-\frac{1}{N_d(0) J}} \cong T_K, \tag{3}$$

in accordance with qualitative considerations.

This model is also convenient for examining various physical properties. It turns out that the thermodynamic characteristics (the large jump in the heat capacity, ΔC;

the thermodynamic critical field H_c; and the correlation length) are determined primarily by the mass of the heavy component of the pair, $m_f \gg m_d$. That this is the case can be verified easily by working from the Ginzburg–Landau functional (cf. Ref. 7). For example, in the limit $T \to T_c$ the correlation length is $\xi_0(T) = \sqrt{7\xi(3)}/2(p_F/\pi m_f)\sqrt{T_c}/T_c - T$. The large jump in the heat capacity is $\Delta C = [2/7\xi(3)] \times p_F(m_f + m_d)T_c$, but the heat capacity itself is also determined by the heavy mass. As a result, the ratio $\Delta C/\gamma T_c$ is precisely the same (1.43) as in the BCS theory. On the other hand, an analysis of the electrodynamic response shows that at low temperatures this response is determined by the light mass, m_d. The simplest way to verify this assertion at a qualitative level is to work from the ordinary coupling $\mathbf{j} = -\Sigma_i(ne/m_i)\langle \mathbf{p} + \frac{e}{c}\mathbf{A}\rangle \cong -(ne^2/m_d c)\mathbf{A}$, where we are using the stiffness of the wave function. The screening of the field is thus performed by the "light," component of the pair, and we have $\lambda_L^2(0) = m_d c^2/4\pi ne^2$.

Up to this point we have been considering the case of the simple interaction in (1). Our general analysis of irreducible interaction vertices in various channels (intraband and interband, singlet and triplet), with allowance for the Coulomb and electron-phonon interactions, shows that the effective interaction renormalized in this fashion is attractive in the singlet interband channel. The Coulomb interaction does not change that result.

It can also be known that the critical temperature for the superconducting transition for interband singlet pairing is above the temperature of the corresponding triplet pairing in the heavy component.

We conclude with a summary of some of the attractive features of this model:

1. It explains in a natural way the superconductivity in heavy-fermion systems, e.g., $CeCu_2Si_2$, and its absence in $LaCu_2Si_2$, which is an isomorphic compound without f-electrons.

2. There is no need to appeal to any special mechanism to cause the pairing. The mechanism which is primarily responsible for the superconductivity is the same antiferromagnetic f-d interaction which is always used to explain the normal properties of these systems.

3. The superconductivity is of an ordinary singlet nature, in agreement with the experimental conclusions of Ref. 3, at least with regard to $CeCu_2Si_2$.

4. The thermodynamic and electromagnetic properties are interpreted in accordance with experiment.

5. One can use this model for an attempt, admittedly quite speculative at this point, to also explain the nonexponential dependence of various quantities below T_c (Refs. 1–3): If interband pairing does occur, it will be most effective where there is an intersection (or nesting) of the Fermi surfaces of the f- and d-components. In this case, as in the formation of charge density waves in systems of the $NbSe_2$ type, if the nesting is incomplete the gap forms over only part of the Fermi surface, rather than over the entire Fermi surface. This result may be manifested by a nonexponential behavior of various properties below T_c. We mentioned above a preliminary experi-

mental indication[3] that some of the electrons remain in the normal state down to $T \ll T_c$; this fact could be explained in a natural way in the picture proposed here.

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