Heavy-electron superconductors, spin fluctuations, and triplet pairing

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The interactions in heavy-electron fluctuating-valence metals are discussed. The conclusion is that the state is closely analogous to "Brinkman-Rice" Fermi liquids like ^{3}He in which parallel-spin effective interactions are attractive and antiparallel interactions strongly repulsive; hence, "triplet"—actually odd-parity—superconductivity is the most likely possibility.

In the past year or so it has become accepted that a number of compounds of U and Ce can almost certainly be best described as "Kondo lattices" in which the magnetism of the f-shell ion is quenched by the Kondo effect, leaving behind a Fermi liquid of extremely heavy electrons.[1] Of these compounds—e.g., $CeAl_3$, $CeCu_2Si_2$, UBe_{13}, UPt_3—several become superconducting between 1 and 0.1 K. The purpose of this paper is to point out that these compounds can be put in close analogy with the heavy Fermi liquid ^{3}He, and that analogous interactions to that case lead with high probability to "triplet" superconductivity. Varma[2,3] has already proposed this possibility for related reasons, and pointed out that none of the known experimental data exclude, and some favor, the triplet possibility. Varma has also made a careful study of possible experimental tests for triplet superconductivity.

I use the term "triplet" here but, of course, in the presence of strong spin-orbit coupling, the only reliable symmetries are time reversal and parity, and the cleanest description is to call it "odd-parity" superconductivity, made up of pairs which are parity odd like $L=1$ pairs in ^{3}He. In the simplest "unitary" case the pairs are also *even* under time-reversal symmetry. (Note that evenness under T means that conventional weak superconducting junctions to singlet superconductors will not work; however, nonunitary phases such as one expects in a magnetic field can make junctions to ordinary superconductors.)

Already Castaing,[4] a number of years ago, characterized liquid ^{3}He as a "Kondo liquid," but his ideas have not gained general acceptance. The substance of these ideas may well have been contained in the view of Brinkman and Anderson[5] of ^{4}He as a Brinkman-Rice[6] Fermi liquid which is close to a Mott paramagnetic or antiferromagnetic insulator such as solid ^{3}He, rather than "almost ferromagnetic" as is envisaged in the conventional spin fluctuation point of view. Vollhardt[7] has recently reemphasized this point. The characteristic sign of Brinkman-Rice behavior is the fact that the "Stoner enhancement" factors takes on a constant value, near 4 for all pressures, rather than diverging as the effective mass appears to be doing as the paramagnetic instability is reached. Castaing's point, which is to a certain extent well taken, is that this constant Stoner enhancement is due to a very similar mechanism to the famous Wilson enhancement factor 2 in the Kondo effect: the *local* spin fluctuations are enhanced relative to the noninteracting Fermi liquid because opposite-spin fermions cannot occupy the same site.

Although we have, at the moment, no complete formal theory of the Kondo lattice, we do have a number of hints towards a theory, and the application of these hints to these materials has been started by Razafimandaby, Fulde, and Keller.[8] As they do, we will suppose that the Kondo ions can be treated by the Nozières "Fermi-liquid" ansatz,[9] with only the slightest modification due to the interaction of the ions. Since the Fermi-liquid parameters in Nozières' representation are mostly determined by general sum rules rather than by detailed dynamics, this seems to be a sound procedure. In particular, band formation is not expected to modify very much the Friedel sum rule which determines the phase shifts at the Fermi surface, especially if a "muffin-tin" approximation is fairly accurate.

We concentrate, however, on the interaction parameter which determines the Stoner enhancement. Just as for the single Kondo impurity, we know that this interaction is effective only in the opposite-spin channel (we concentrate here on the simple case of $CeCu_2Si_2$ where crystal-field interactions leave us with a doublet ground state and we speak of the two channels of the doublet as "opposite spin"). We have, then, precisely the short-range hard-core interaction which is assumed in the conventional diagrammatic theory of ^{3}He. In that theory (see Brinkman and Anderson) the effective repulsive coupling for antiparallel spin fermions is called I and the interaction which enters the Stoner enhancement parameter $\bar{I}=N(0)I\simeq\frac{3}{4}$. We have

$$\chi=\frac{\chi_0(\text{density of states})}{1-\bar{I}}.$$

The effective interaction, then, after resummation of the appropriate diagrams, is

$$V(q,\omega)=-\frac{1}{2}\frac{I}{1-I\chi_0(q,\omega)}$$
$$=-\frac{1}{2}\frac{I}{1-\bar{I}[\chi_0(q,\omega)/\chi_0(0,0)]}.$$

This is then attractive and quite large. Since $N(0)I\cong\frac{3}{4}$, $V\cong 3E_F/4$ and the big problem in helium is to reduce the attractive interaction to manageable size so that $T_c/E_F\sim 10^{-2}$, as is the case. This reduction has been plausibly carried out by a number of authors, Levin and Valls[10] in particular, using corrections which are mostly special to the ^{3}He case in which there are giant hard cores leading to very high compressibility forces and large steric hindrance factors. One may parametrize these effects by rather small upper momentum cutoffs for the spin-fluctuation effects. Another way of putting it is that, one way or another, these effects must be reduced by wave-function renormalization factors.

In the case of the heavy electron materials, again $N(0)I$ can be expected to be of order unity, and the interaction will again be enhanced by whatever Stoner factor is appropriate—even 4 in the Kondo-like case of $CeCu_2Si_2$. (The actual observed enhancement of χ is complicated by spin-orbit effects.) We would claim that the appropriate fixed point to describe the ground state of the Kondo lattice is the Brinkman-Rice liquid. There are no enormous hard cores or steric factors to reduce the interaction pseudopotential (contrary to Fulde and co-workers, this pseudopotential is *short range,* existing only at the individual f-shell ion). This is why $T_c/E_F \sim 0.1$, an order of magnitude larger than in ^{3}He. The reason why it is not even larger is likely to be that the interaction takes place only on the f-shell ions which are a minority of the atoms; hence, it is reduced by something like the relative concentration of Ce or U. Even though the large renormalization factor tells us that the electron spends most of its *time* in the Kondo resonance, the effective wave function spreads throughout the lattice and I believe the effective interaction is correspondingly reduced: that is, it is a pseudopotential with an effective length a of one atomic size, not several. Thus, the T_c's are quite reasonable: relatively larger than ^{3}He, but a few factors less than $T_F =$ the bandwidth.

Following are a few final remarks. First, it is clear that we are proposing the first nonphonon mechanism for superconductivity. Unfortunately, it occurs only in substances where $T_F << \theta_D$, the Debye temperature; hence it is not yet a candidate for high-temperature superconductivity. As T_K gets larger we expect strong phonon effects of a controversial nature to occur. Clearly the Anderson lattice-type mixed valence metals with $T_F > \theta_D$ are not superconducting, for reasons not obvious to us at this time. Phonon interactions may be pair breaking for triplets.

What about phonon interactions? We believe these to be quite weak in the heavy-fermion materials on the basis that T_K is so small compared to θ_D. This clearly implies that conventional phonon effects are small in that the *phonon* phase space is mostly unusable. In addition, the actual amount of f occupation change upon creating a given electron is small like $Z \sim 1/m_{\text{heavy}}$. Experimentally, phonon-electron interactions seem to be small. The Kondo volume effect proposed by Fulde is quite real in the Anderson lattice cases like Ce, but not where $T_K << \theta_D$, since the amount of energy involved in the Kondo effect is too small to strain the lattice appreciably. Thus, the Kondo volume effect does not occur in such pure Kondo-like cases as SmB_6 and $CeAl_3$, and will not occur in UBe_{13}, etc.

Finally, it is not clear why other Brinkman-Rice liquids such as V_2O_3 under pressure are not triplet superconductors also; of course, in such cases phonon effects, which we do not consider, are important.

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