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Further consequences of symmetry in heavy-electron superconductors

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The energy-gap symmetry is severely constrained by the physical assumption that the attractive interaction involves f-electron pairing in the f-shell heavy-electron superconductors. This suggests that odd-parity ("triplet") superconductors must have at least two f-shell atoms per unit cell.

In earlier papers[1,2] we showed that (a) the most likely source of the attractive interaction responsible for superconductivity in the heavy-electron superconductors UBe_{13}, UPt_3, $CeCu_2Si_2$, etc., is the f-f interaction due to the localized spin fluctuations in the f shell, and (b) that in the presence of strong crystal fields and spin-orbit coupling, possible phases of these superconductors must be classified according to triplet, odd-parity representations of the point group of the crystal. Blount[3] has expanded on this classification and described the group theory of such phases.

Here we discuss an additional interesting consequence of symmetry. If we believe that the interaction is localized on the f-shell ions, it is only in or near these ions that the gap function $\Delta(r,r',\sigma,\sigma')$ is appreciably large. A second point is that the attractive interaction is almost certainly an f-f pair interaction, since free-electron–f-electron interactions are either repulsive (if Coulomb) or strongly weakened by renormalization (if phonon mediated). But bound pairs of f electrons necessarily are of even parity about the atom on which they reside, by the rule $P=(-1)^{\Sigma l_i}$.

This point of view tells us that either (a) the superconductivity is, after all, singlet, even-parity, BCS superconductivity, or (b) there are two or more f atoms per unit cell in the crystal structure, related in pairs by inversion in a center of symmetry. On each atom, Δ must have the form of an f-f bound-pair state, but the sign of $\Delta(r,r')$ at one site A must be the opposite to that at the other site B:

$$\Delta_A(r,r') = -\Delta(-r,-r') = -\Delta_B \quad . \tag{1}$$

Only by having a center of symmetry external to the f-shell ions can we have an odd-parity gap function.

In fact, all of the supposed cases of heavy electron superconductivity (UBe_{13}, UPt_3, $CeCu_2Si_2$) have the appropriate crystal structure, while crystals such as $CeAl_3$ which have very heavy electrons but no such center of symmetry are not superconducting. It will be fascinating to see if this structural conjecture continues to hold up.

It is not easy to see what other consequences will result. Contrary to our own early speculations, while such a gap structure is likely to lead to point zeros on the Fermi surface, it does not give lines of exact zeros, and therefore does not explain the observations of specific heat[4] or acoustic attenuation.[5]

On the other hand, in view of the complexity of the gap-function structure, it is unlikely that any simple model of "Anderson-Brinkman-Morel–like" or "polar" gaps is at all relevant to the observations, either. What we can be sure of is that $|\Delta(k)|$ has a very wide variation which can be modeled in no simple way.

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