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Josephson Effects in Superconducting Conventional/Unconventional Tunnel Junctions and Weak-links

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The a.c. Josephson effect is perhaps the most striking manifestation of long-range phase coherence (broken gauge symmetry) in superconductors. Superconductivity in which gauge symmetry is broken in combination with one or more additional symmetries of the normal metallic state (*unconventional* superconductivity) may also occur. We discuss the Josephson effect for several models of an unconventional superconductor in contact with a conventional superconductor. An unconventional order parameter leads to qualitative changes in the current-phase relation which could be detected with a SQUID in which one arm of the interferometer is an unconventional superconductor. We also compare the current-phase relation for a tunnel junction with that of a weak-link connecting a conventional and unconventional superconductor. Selection rules for unconventional order parameters which enforce zero supercurrent in a tunnel junction are not relevant for weak-links connecting the same unconventional and conventional superconductor. We discuss the the a.c. Josephson effect for several popular models of unconventional superconductivity relevant to the CuO and heavy fermion superconductors.

In this paper we discuss some special aspects of Joesphson tunneling involving an unconventional superconductor, and consider their experimental implications. We illustrate our points by considering some popular model order parameters for the heavy fermion superconductors and the oxide superconductors.

In a tunneling geometry surfaces are unavoidable. These surfaces have non-trivial effects on the unconventional superconductor. Rough surfaces are always pair-breaking. Even smooth surfaces are pair-breaking except in special orientations where the order parameter only has orbital components that are parallel to the surface. Thus, the order parameter at the surface is generally different from that in the bulk. We have investigated the effect of surface pair-breaking on the critical current [1]. To analyze the current-phase relation for Josephson junctions involving unconventional superconductors it is important to know the symmetry and behavior of the order parameter at the interface. However, knowledge of $\Delta(\hat{k}, \vec{R}_{surf})$ alone may be insufficient, and in some cases misleading. The Josephson current is actually determined by the off-diagonal Green's function at the interface, not $\Delta(\hat{k}, \vec{R}_{surf})$. As an example consider Josephson tunneling between two superconductors, both of which have an order parameter $\Delta(\hat{k}) \sim \hat{k}_z(\hat{k}_x + i\hat{k}_y)$ in the bulk, coupled through a smooth junction in the x-y plane. The order parameter on both sides necessarily vanishes at the interface. However, the off-diagonal Green's functions do not vanish at the junction. In fact they are odd in frequency and even in $\hat{k}_z$ at the interface, which is opposite to their behavior far from the interface. Moreover the critical current is not small, but comparable with J_c for general orientations where the order parameters do not vanish at the junction interface [1].

The defining property of an unconventional superconducting order parameter is that it break one or more symmetry operations of the crystal, *i.e.* a rotation or a reflection symmetry. We consider the consequences of such broken spatial symmetries for the Josephson current in two specific examples.

An order parameter belonging to one of the 2D representations has been proposed for superconducting UPt_3. There are two possible candidates (four including parity): E_1 or E_2. The most popular ground-state order parameter for the E_1 (E_2) representation, $\hat{k}_z(\hat{k}_x \pm i\hat{k}_y)$ ($(\hat{k}_x \pm i\hat{k}_y)^2$), acquires a phase change of $\frac{\pi}{3}$ ($\frac{2\pi}{3}$) under a $60°$ rotation about the $\hat{c}$ axis. Consider two junc-

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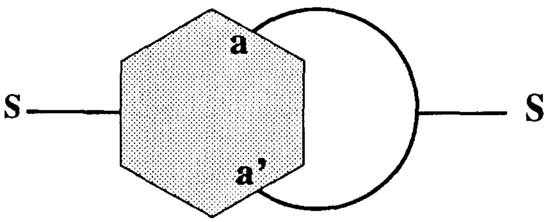
tions between UPt_3 with an s-wave superconductor on two different faces of the hexagonal crystal, a and a'. The junctions are related by a 120° rotation, but are otherwise identical. The crucial point is that under a 120° rotation the order parameter for the model of UPt_3 undergoes a phase change. Equivalently, the 120° rotation followed by a gauge transformation of $\phi_u \rightarrow \phi_u - 2\mu\pi/3$ is a symmetry operation. Thus, we have for the supercurrents at a and a',

$$I_a(\phi_u - \phi_s) = I_{a'}(\phi_u - \phi_s + \frac{2\mu\pi}{3}), \qquad (1)$$

where ϕ_s is the phase of the s-wave order parameter, and $\mu = 1$ and 2 for the E_1 and E_2 representations, respectively. This symmetry has an interesting experimental consequence. Consider the SQUID constructed from these junctions (Fig. 1).



1. SQUID geometry for U|S junctions.

Equation (1) implies that the maximum critical current for the SQUID occurs for an external flux $\Phi = (n + \frac{\mu}{3})\Phi_o$ where n is an integer and Φ_o is the flux quantum in superconductivity. This interference pattern is a signature of broken rotational symmetry and would allow us to distinguish between the E_1 and E_2 representations. Possible generalizations of this experiment are obvious, *e.g.* a Josephson interference experiment can be used to test the parity of a superconductor. This idea has also been pursued experimentally to test for a $d_{x^2-y^2}$ order parameter in the oxide superconductors [2]. Note that there are orientations of a junction at which the critical current vanishes, so one has to choose appropriate interfaces to make such a test feasible.

The broken symmetry of an unconventional order parameter often imposes 'selection rules' for the Josephson current. Consider a tunnel junction between a superconductor with order parameter $\Delta_d \sim \hat{k}_x^2 - \hat{k}_y^2$ and phase ϕ_d, and an s-wave superconductor with phase ϕ_s. Assume the junction is in the x-y plane. A rotation about the $\hat{c}$ axis changes the sign of the d-wave order parameter, *i.e.*, $\phi_d \rightarrow \phi_d + \pi$, whereas the s-wave order parameter and the currents are invariant, thus

$$I(\phi_d - \phi_s) = I(\phi_d - \phi_s + \pi). \qquad (2)$$

For an ideal tunnel junction, the expression for the Josephson current depends on the phase difference of the order parameters on the two sides only through the terms $\sim \Delta_d^*\Delta_s$ or $\sim \Delta_s^*\Delta_d$ to the *first* power. Hence the critical current vanishes by symmetry. However, Eq. (2) does not forbid a Josephson coupling [3]. In fact, for a 'weak-link' (SNS junctions or microconstrictions) the critical current is finite. A straigtforward calculation for the case of a pinhole [4] shows that the Josephson current is indeed finite, though periodic in the phase difference with a period of π as demanded by Eq. (2). This critical current is not small, but of order of $\sim (\Delta_d\Delta_s)^{1/2}/R$, where R is the normal-state resistance of the weak-link. Thus, for weak-links the presence or absence of a supercurrent provides no information on the symmetry of the order parameters involved. This information is contained in the period of the current-phase relation. Thus, a study of the Shapiro steps is important for examining the symmetry of a candidate unconventional superconductor.

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