Josephson effect in superconductors with odd pairing

M. V. Sadovskiĭ[1)]

Institute of Electrophysics, Ural Mountain Branch of the Russian Academy of Sciences, 620219 Ekaterinburg, Russia

(Submitted 14 December 1994)
Pis'ma Zh. Eksp. Teor. Fiz. **61**, No. 2, 122–123 (25 January 1995)

The Josephson current vanishes in an S–I–S geometry if one or both of the superconductors have a gap which is odd in $p-p_F$. For pairing with a gap which is odd in frequency, the Josephson current vanishes for a junction of an ordinary superconductor with an odd one. It does not vanish for a junction with two odd superconductors.

Some unconventional models of "odd" pairing in superconductors have recently been studied quite actively.[1–5] These models are attractive for explaining the physical properties of some unusual superconductors (high-T_c superconductors and heavy-fermion systems) which have been discovered and also in connection with the search for new systems with a superconducting state with anomalous properties. Here it is particularly important to formulate some simple experimental criteria which would make it possible to unambiguously identify the type of anomalous pairing.

In this letter we examine distinctive features of the Josephson effect in S–I–S junctions containing odd superconductors. We start with a standard analysis of the Josephson effect within the formalism of tunneling Hamiltonian.[6] Corresponding calculations show that the Josephson current through the junction can be expressed in the standard form

$$I=I_c\sin(\phi_1-\phi_2), \tag{1}$$

where ϕ_1 and ϕ_2 are the phases of the order parameter (the gap) in S contacts 1 and 2, and the critical current I_c is given by the general expression

$$I_c=4e\sum_{\mathbf{pq}}|T_{\mathbf{pq}}|^2T\sum_{\omega_n}F_1^*(\mathbf{p},\omega_n)F_2(\mathbf{q},-\omega_n). \tag{2}$$

Here $T_{\mathbf{pq}}$ is a matrix element of the tunneling of an electron through the insulating layer. The anomalous Matsubara-Gor'kov functions $F_{1,2}(\mathbf{p},\omega_n)$ are given by expressions of the type

$$F(\mathbf{p},\omega_n)=\frac{\Delta(\mathbf{p},\omega_n)}{\omega_n^2+\xi_{\mathbf{p}}^2+\Delta^2(\mathbf{p},\omega_n)}. \tag{3}$$

Here $\Delta(\mathbf{p},\omega_n)$ is the gap function; $\omega_n=(2n+1)\pi T$ (T is the temperature); e is the charge of an electron; and $\xi(\mathbf{p})=v_F(|\mathbf{p}|-p_F)$ is the excitation energy of the electrons near the Fermi level in the normal state of the superconductor.

We first consider a pairing scheme which is odd in $p-p_F$ (Refs. 1, 3, and 4). In this case we have

$$\Delta(\mathbf{p},\omega_n)=\Delta(\xi_{\mathbf{p}})=-\Delta(-\xi_{\mathbf{p}}). \tag{4}$$

The pairing is isotropic, and expression (2) reduces in the usual way to the form[6]

$$I_c=\frac{T}{\pi eR}\sum_{\omega_n}\int_{-\infty}^{\infty}d\xi_p\int_{-\infty}^{\infty}d\xi_q F_1^*(\xi_p,\omega_n)F_2(\xi_q,-\omega_n), \tag{5}$$

where R is the resistance of the tunnel junction, expressed in terms of the matrix element $T_{\mathbf{pq}}$, averaged over the Fermi surface of each of the superconductors. It is easy to see that expression (5) vanishes because $\Delta(\xi_p)$ is odd in the variable ξ_p [see (4)], both in the case in which one of the superconductors is odd and in the case in which both the S junctions are odd. The transformation from (2) to (5) and, correspondingly, the assertion which we just made are of course valid if we ignore the change in the matrix element $T_{\mathbf{pq}}$ over scales on the order of the Fermi energy E_F, and if I_c vanishes within terms on the order of T_{pq}^2/E_F^2. From the experimental standpoint, these conditions of course mean that the Josephson effect is suppressed essentially almost completely.

We now consider the case of a pairing which is odd in the frequency.[2,3,5] In this case we have

$$\Delta(\mathbf{p},\omega_n)=-\Delta(\mathbf{p},-\omega_n). \tag{6}$$

We then see from general expression (2) that I_c vanishes if one of the S junctions is an odd superconductor. If both junctions are odd, we obtain a final expression for I_c whose explicit form depends on the particular model of the odd pairing.[2,5] It can be used to study the corresponding order parameter. The reason why I_c vanishes in the case of superconductors of different parities in this case is that a gap which is odd in the frequency breaks T parity, while the tunneling Hamiltonian is invariant under time reversal.[6]

This study was carried out as part of Project 93-001 of the State Program of Research on High-Temperature Superconductivity.

[1)]E-mail: sadovski@ief.e-burg.su

[1]F. Mila and E. Abrahams, Phys. Rev. Lett. **67**, 2379 (1991).
[2]A. Balatsky and E. Abrahams, Phys. Rev. B **45**, 13125 (1992).
[3]E. Abrahams, J. Phys. Chem. Solids **53**, 1487 (1992).
[4]É. Z. Kuchinskiĭ *et al.*, Zh. Eksp. Teor. Fiz. **104**, 3550 (1993) [JETP **77**, 692 (1993)].
[5]P. Coleman *et al.*, Phys. Rev. B **49**, 8995 (1994).
[6]I. O. Kulik and I. K. Yanson, *Josephson Effect in Superconducting Tunneling Structures* (Halsted, New York, 1972).

Translated by D. Parsons