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Josephson current in ferromagnetic d-wave superconductor/ferromagnetic d-wave superconductor junction

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Abstract

We solve a self-consistent equation for the d-wave superconducting gap and the effective exchange field in the mean-field approximation, study the Zeeman effects on the d-wave superconducting gap and thermodynamic potential. The Josephson currents in the d-wave superconductor (S)/insulating layer (I)/d-wave S junction are calculated as a function of the temperature, exchange field, and insulating barrier strength under a Zeeman magnetic field on the two d-wave Ss. It is found that the Josephson critical currents in d-wave S/d-wave S junction depend to a great extent on the relative orientation of the effective exchange field of the two S electrodes, and the crystal orientation of the d-wave S. The exchange field can under certain conditions enhance the Josephson critical current in a d-wave S/I/d-wave S junction.

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1. Introduction

Recently, the coexistence of superconductivity and ferromagnetism has been an interesting subject in condensed matter physics [1–4]. Following the original work of Clogston [5] and Chandrasekhar [6], the modification of superconductivity by the Zeeman coupling between the spins of the electrons and applied magnetic field has attracted intermittent attention [7]. A more unusual aspect of this physics was uncovered by Fulde and Ferrell [8] and Larkin and Ovchinnikov [9] (FFLO) that a finite momentum pairing state can occur under magnetic fields when electron momenta at the Fermi energy are different for the two spin directions, the FFLO state is predicted for a clean spin-singlet superconductor (S) as a result of the competition between pairing correlations, favoring antiparallel spin alignment and the Zeeman effect, favoring parallel spin alignment along the field. Experimentally, the classic predictions on the nature of the s-wave phase boundary have been confirmed by the work on thin Al films [10]. A number of layered organic Ss have been suggested as candidate for FFLO phase [11–13]. However, recent interest has focused on the heavy fermion material $CeCoIn_5$, because several measurements have led to a renewed discussion of a possible high field FFLO state [14–18]. $CeCoIn_5$ has quasi-two-dimensional metallic planes, and shows evidence of unconventional d-wave superconductivity [19–24] with a transition temperature of $T_c = 2.3$ K. Unlike the conventional Cooper pair in which two electrons have opposite spins and momenta ($\mathbf{k}\uparrow, -\mathbf{k}\downarrow$), the Cooper pair in the FFLO state has a finite centre-of-mass momentum of the order of $2h_0/\hbar v_F$, and consequently leads to a spatially modulated superconducting order parameter, where h_0 is the magnetic exchange energy corresponding to the half of the difference in the energy between the spin-up and spin-down bands, and v_F is the Fermi velocity. For a two-dimensional d-wave S, the superconducting state responds non-trivially at arbitrarily small values of the magnetic field due to the existence of gap nodes, so that electron

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spins may be polarized with little cost in energy. The response of a d-wave S to a Zeeman magnetic field should provide a possible candidate to study the coexistence of superconductivity and ferromagnetism.

The Josephson effect has attracted much attention since the Josephson effect was discovered in S/S junction, and there has been a continuously growing interest in the fundamental physics and the application of this effect. In recent years, the ferromagnet (F) has been introduced to the Josephson tunnel structure, giving rise to some new physical effects. As an example, if very thin insulating layer in a S/I/S junction is replaced by thin ferromagnetic layer (with I denoting an insulating layer), a new type of S/F/S Josephson junction is formed [25–29]. At the same time, Bergeret et al. [30] and Li et al. [31] proposed a Josephson tunnel junction of two F/S bilayers separated by a thin insulating film. On the assumption that a thin F/S bilayer is equivalent to a homogeneous ferromagnetic superconductor (FS), the S/F/I/F/S structure may be simplified as a FS/FS junction. They found that the presence of an exchange field may increase the critical current in the FS/FS junction in the case of an antiparallel alignment of the magnetization in the ferromagnets at low temperature and strong barrier strength. Above these theories only dealt with isotropic ferromagnetic s-wave S(FsS), but the Josephson current in ferromagnetic d-wave superconductor (FdS)/FdS has not yet been studied. It is known that the transport properties in d-wave S junctions are quite different from the s-wave S junctions. In a–b plane junction of the d-wave S, not only the magnitude of the pair potential, but also the orientation of the S crystal with respect to the interface normal influence significantly the Josephson current in the junctions. It is highly desirable to clarify the Josephson currents depend on the relative orientation of the effective exchange field of the two FdS electrodes, and the crystal orientation of the d-wave S in such a FdS/FdS junction, as well as its dependence on the temperature, barrier strength.

The purpose of this Letter is twofold. The first one is to study the response of a d-wave S to a Zeeman magnetic field. We solve self-consistent equations for the d-wave superconducting gap and the magnetization in the mean-field approximation, and calculate the difference in thermodynamic potential between the FdS and normal states. The other purpose of this Letter is to present the Josephson current in FdS/FdS junction by applying an extended Furusaki and Tsukada (FT) approach [32]. The analytic expressions for the Josephson current in parallel and antiparallel alignments of the magnetizations in two FdS's are obtained as functions of the temperature, exchange field, and insulating barrier strength. It is found that the Josephson critical currents in FdS/FdS junction depend to a great extent on the crystal orientation of the d-wave S and the relative orientation of the effective exchange field of the two FdS electrodes. The presence of an exchange field usually suppresses the Josephson critical current in FdS/FdS junction. The only exception is that the critical current increases with increasing exchange field for $\alpha = 0$ (α the angle between the a axis of the d-wave S crystal and the interface normal, as shown in Fig. 1), one needs low temperatures, strong barrier strength, and an antiparallel configuration. In the case of $\alpha \neq 0$, however, the enhancement of Josephson critical current only on condition of weak barrier strength, low temperatures, and the parallel configuration of the two FdS electrodes.

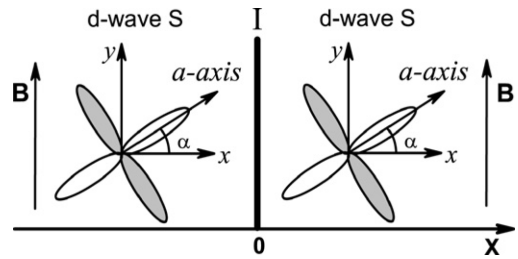

Fig. 1. Schematic illustration of the model for d-wave S/I/d-wave S junction, in which α the angle between the a axis of the d-wave S crystal and the interface normal, $\mathbf{B}$ is the applied magnetic field along the y-axis direction.

2. Zeeman effects on d-wave S

Consider a two-dimensional d-wave S/I/d-wave S structure, in which the left and right electrodes are made of the same d-wave S, and they are separated by very thin insulating layer. The thin insulating layers at $x = 0$ can be modeled to be a δ-type barrier potential $U(x) = U_0\delta(x)$, where U_0 depends on the product of barrier height and width. As in the previous works [33,34], we neglect for simplicity the self-consistency of spatial distribution of the pair potential in S and take them as a step function $\Delta(x) = \Delta[e^{i\phi_L}\Theta(-x) + e^{i\phi_R}\Theta(x)]$, where Δ is the pair potential for a d-wave S, ϕ_L and ϕ_R stand for the macroscopic phase of the left and right S, respectively. There is a uniform magnetic field $\mathbf{B}$ applied to d-wave S along the y-axis direction, as shown in Fig. 1, the Zeeman energy $h_0 = \mu B$, where $\mu = g\mu_B/2$ is the magnetic moment of an electron, μ_B is the Bohr magneton, g is the factor of the paramagnetic centre. The Hamiltonian of the system is expressed as

$$H = \sum_{\mathbf{k}\sigma} \varepsilon_k c^+_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \sum_{\mathbf{k}} h_0\left(c^+_{\mathbf{k}\uparrow}c_{\mathbf{k}\uparrow} - c^+_{\mathbf{k}\downarrow}c_{\mathbf{k}\downarrow}\right) + \sum_{\mathbf{k}\mathbf{k}'} V_{\mathbf{k}\mathbf{k}'} c^+_{\mathbf{k}\uparrow} c^+_{-\mathbf{k}\downarrow} c_{-\mathbf{k}'\downarrow} c_{\mathbf{k}'\uparrow}, \tag{1}$$

where $\varepsilon_k = \hbar^2k^2/(2m) - E_F$ is the kinetic energy measured relative to the Fermi energy E_F, $V_{\mathbf{k}\mathbf{k}'}$ is the attractive potential between the conducting electrons, and $V_{\mathbf{k}\mathbf{k}'} = -2V_0\cos[2(\phi_k - \phi_{k'})]$ with V_0 is the strength of the effective attractive potential between the conducting electrons, $\phi = \arctan(\hat{\mathbf{k}}_x/\hat{\mathbf{k}}_y)$ is the azimuthal angle of $\mathbf{k}$. Under the self-consistent field and the mean-field approximation, by means of a Bogoliubov transformation:

$$\gamma_{\mathbf{k}\sigma} = u_k c_{\mathbf{k}\sigma} - \eta_\sigma v_k c^+_{-\mathbf{k}\bar{\sigma}}, \tag{2}$$

$$u_k^2 = (1 + \varepsilon_k/\xi_k)/2, \tag{3}$$

$$v_k^2 = (1 - \varepsilon_k/\xi_k)/2. \tag{4}$$

Hamiltonian (1) can be diagonalized as [35]