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Critical currents in Josephson junctions with $d + \mathrm{i}s$ symmetry

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Abstract

The magnetic interference pattern and the spontaneous flux in unconventional Josephson junctions of superconductors with $d + \mathrm{i}s$ symmetry are calculated for different reduced junction lengths. The asymmetry in the field-modulated diffraction pattern exists for lengths as long as $L = 10\lambda_J$. This is a time-reversal broken symmetry state. We present the evolution of the overlap critical current as a function of the crystal orientation for the fractional vortex and antivortex that are spontaneously formed near the junction center. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Critical currents; Josephson junctions; $d + \mathrm{i}s$ symmetry

1. Introduction

Regarding high-T_c superconductors, a large number of experimental results support that the order parameter is of dominant d-wave character [1]. Theories predict that a two-component order parameter is also possible. A number of different states emerges if one takes into account the phase difference between the two parts of the order parameter. The mixing due to orthorhombicity predicts a $d + s$ or equivalently $d - s$ order parameter. In this case, a phase difference of ϕ or π exists between the two components of the order parameter. On the other hand, when the phase difference is $\pi/2$, the $d + \mathrm{i}s$-wave case is considered. This state has the time-reversal symmetry $\mathcal{T}$ broken. Calculations based in BCS weak-coupling theory [2] predict that the $d + \mathrm{i}s$-wave state is realized in a certain range of interaction, in the absence of any orthorhombic distortion. Also, the observation of fractional vortices on the grain boundary in $YBa_2Cu_3O_7$ by Kirtley et al. [3], may indicate a possible violation of the time-reversal symmetry near grain boundary. In addition to that, magnetic impurities are another source of time-reversal symmetry violation [4]. Therefore, it is interesting to study more this symmetry in the case of interfaces.

2. Junction geometry

We consider the superconductors (A and B), which are separated by an intermediate layer of thickness t in the z direction, as seen in Fig. 1a. Each superconductor has a two component order parameter $(n_1^{A(B)}, n_2^{A(B)})$, $n_i^\mu = \tilde{n}_i^\mu e^{i\phi_i^\mu}$, $\mu = $ A,B, where $\tilde{n}_1^\mu =$

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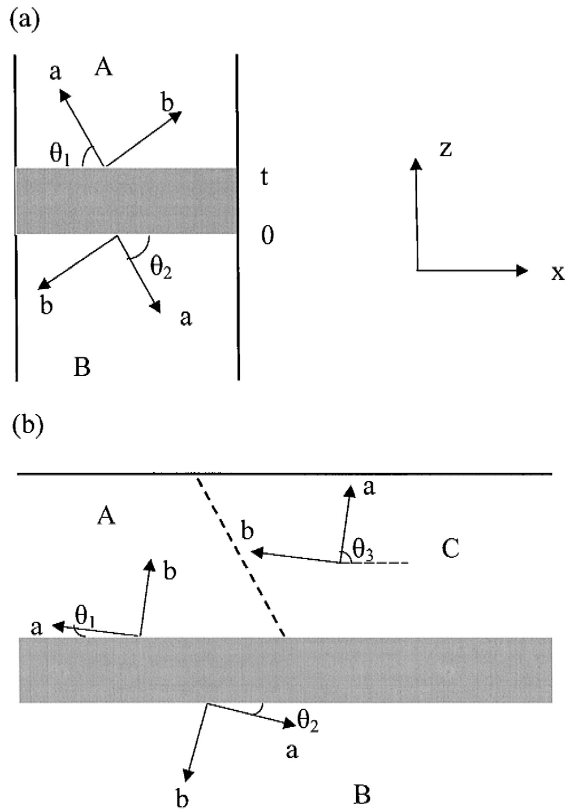

Fig. 1. (a) A single Josephson junction between superconductors A and B with a two-component order parameter. The angle between the crystalline a axis of A(B) and the junction interface is $\theta_1(\theta_2)$. (b) The geometry of the junction between the twinned crystal (regions A and C) and the untwinned crystal B. The dashed line marks the twin boundary.

$n_{10}\ \cos(2\theta)$, $\tilde{n}_2^{\mu} = n_{20} =$ constant, are the order parameter magnitudes for the d- and s-wave, respectively, and ϕ_1^{μ}, ϕ_2^{μ}, are the corresponding phases. The d-wave component depends on the angle θ of the crystalline a-axis with respect to the junction interface. For $d+\mathrm{i}s$-wave case the intrinsic phase difference within each superconductor A and B can be assumed to be $\phi_2^{\mathrm{A}} - \phi_1^{\mathrm{A}} = \phi_2^{\mathrm{B}} - \phi_1^{\mathrm{B}} = \pi/2$. Then the supercurrent density as a function of the phase difference of the d-wave order parameter between the two superconductors $\phi = \phi_1^{\mathrm{B}} - \phi_1^{\mathrm{A}}$ can be written as [5]

$$J = \sum_{i,j=1}^{2} J_{\mathrm{cij}} \sin\left(\phi_i^{\mathrm{B}} - \phi_j^{\mathrm{A}}\right) = \tilde{J}_{\mathrm{c}} \sin(\phi + \phi_{\mathrm{c}}), \quad (1)$$

where $J_{\mathrm{c}ij} \propto \tilde{n}_i^{\mathrm{A}} \tilde{n}_j^{\mathrm{B}}$ denotes the coupling strength between n_i^{A} and n_j^{B},

$$\tilde{J}_{\mathrm{c}} = \sqrt{(J_{\mathrm{c}11} + J_{\mathrm{c}22})^2 + (J_{\mathrm{c}12} - J_{\mathrm{c}21})^2},$$

$$\phi_{\mathrm{c}} = \begin{cases} \tan^{-1}\dfrac{J_2}{J_1}, & J_1 > 0 \\ \pi + \tan^{-1}\dfrac{J_2}{J_1}, & J_1 < 0 \end{cases}, \quad (2)$$

where $J_1 = J_{\mathrm{c}11} + J_{\mathrm{c}22}$, $J_2 = J_{\mathrm{c}21} - J_{\mathrm{c}12}$. The intrinsic phase, ϕ_{c}, depends on the orientation of the crystalline axis of each superconductor with respect to the junction interface.

We consider the junction shown in Fig. 1b, between the twinned crystal (regions A and C) and the untwinned crystal B. The relative phase of the s- and d-wave order parameter in all three superconducting regions is assumed to be $\pi/2$. The relative orienta-

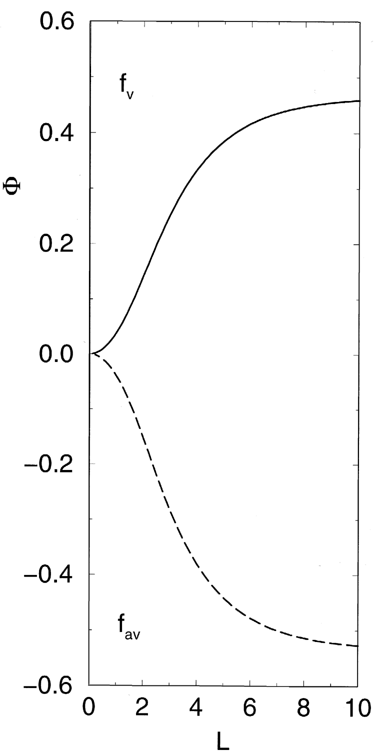

Fig. 2. The spontaneous magnetic flux Φ as a function of the reduced junction length L, for the spontaneous vortex (f_{v}) and antivortex (f_{av}).

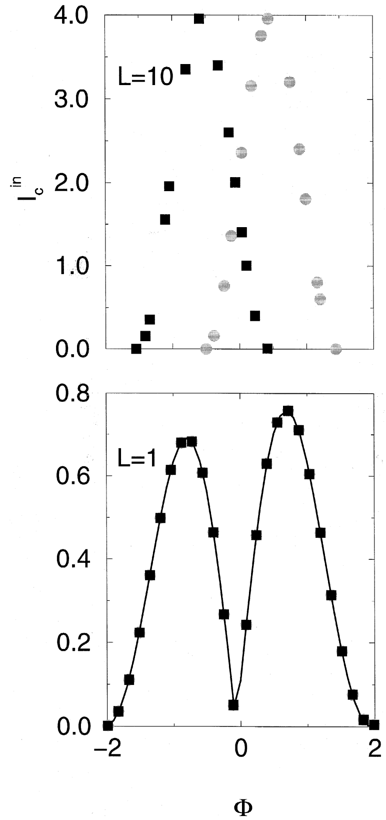

Fig. 3. Inline critical current density I_c^{in} vs. the magnetic flux Φ, $\phi_{c1} = 0.01\pi$, $\phi_{c2} = 1.08\pi$, for different junction lengths: $L = 10$, $L = 1$. The circles (squares) in this figure correspond to the $f_v(f_{av})$ branch.

tion of the a and b axis changes by $\pi/2$ on reflection across the twin boundary. The current transport across the junction is taken to be only along the z direction. We describe the entire junction with width w small compared to λ_J in the y direction, of length L in the x direction, in external magnetic field H in the y direction. The superconducting phase difference ϕ across the junction is then the solution of the sine–Gordon equation

$$\frac{d^2\phi(x)}{dx^2} = \frac{1}{\lambda_J^2}\sin[\phi(x) + \phi_c(x)] + I^{ov},$$

$$\left.\frac{d\phi}{dx}\right|_{x=0,L} = \pm\frac{I^{in}}{2} + H, \tag{3}$$

where $\phi_c = \phi_{c1}$ in $0 < x < L/2$ and $\phi_c = \phi_{c2}$ in $L/2 < x < L$, λ_J is the Josephson penetration depth, $I^{ov}(I^{in})$ is the external overlap(inline) current density. The critical current density $\tilde{J}_c$ depends implicitly on the grain orientation. We can classify the different solutions obtained from Eq. (3) with their magnetic flux content $\Phi = (\Phi_0/2\pi)(\phi_R - \phi_L)$, where $\phi_{R(L)}$ are the values of ϕ at the right (left) edge of the junction, and $\Phi_0 = hc/2e$ is the flux quantum.

In the $d + is$-wave case, where $\phi_{c1} = 0.01\pi$ and $\phi_{c2} = 1.08\pi$, the phase ϕ must form a kink or antikink near $x = 0$ in order to match the conditions on both sides. A new flux quantization appears $\Phi = \chi\Phi_0$ with χ is neither integer nor half-integer. We call the solution with the positive flux as a fractional vortex (f_v) while the negative flux solution is the fractional antivortex (f_{av}). To obtain these vortices as solutions of Eq. (3) for zero current and magnetic field, a kink or antikink like initial condition is used, which is iterated until convergence. Fig. 2 gives the spontaneous flux in junction as a function of the reduced length (L). In Fig. 3, we present our results for the inline critical current density I_c^{in} vs.

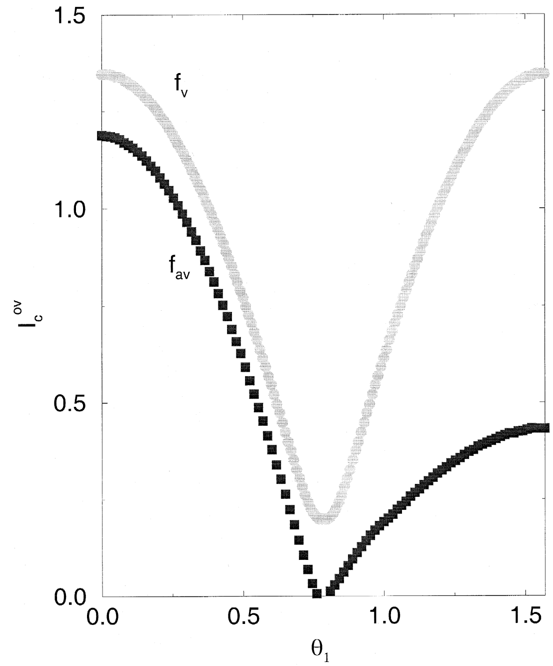

Fig. 4. Overlap critical current density I_c^{ov} vs. the angle θ_1 of the crystalline a-axis of twin A with respect to the junction interface for the f_v, f_{av} solutions, $L = 10$.

the magnetic flux for junction lengths $L=10$, $L=1$. The circles (squares) in this figure correspond to the $f_{\mathrm{v}}(f_{\mathrm{av}})$ branch. In contrast to the pure d-wave case [6], for small lengths this pattern is asymmetric and the ‘‘dip’’ in the maximum current does not occur at $\Phi=0$, but at a finite Φ value. This behavior also exists for lengths as long as $L=10$. In Fig. 4, we plot the overlap critical current density $I_{\mathrm{c}}^{\mathrm{ov}}$ as a function of the angle θ_1 of the twin A with respect to the interface axis, for $H=0$. We see that $I_{\mathrm{c}}^{\mathrm{ov}}$ for the f_{v} has a dip at $\theta_1=\pi/4$. This point corresponds to $\Phi=0$, and in particular, it is a flat phase distribution around $\phi=\pi/2$, and the absence of induced current causes an increase of the critical current, but the almost zero value of $\tilde{J}_{\mathrm{c}}$ reduces the critical current to a minimum at this angle. Similarly, the $I_{\mathrm{c}}^{\mathrm{ov}}$ for the f_{av} branch drops to zero at $\pi/4$, and reaches a minimum at a point where we have a full antifluxon. For angles larger than $\pi/4$, it becomes unstable. As a conclusion, we see a characteristic variation of the critical current with grain orientation that can be checked by experiment.

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