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Extending SQUID interferometry beyond the cuprates and beyond d-wave symmetry

D.J. van Harlingen *, J.E. Hilliard, B.L.T. Plourde, B.D. Yanoff

Department of Physics and the Science and Technology Center for Superconductivity, University of Illinois at Urbana-Champaign, 104 S. Goodwin Avenue, Urbana, IL 61801, USA

Abstract

Phase-sensitive superconducting quantum interference device (SQUID) interferometry measurements have been instrumental in establishing the d-wave pairing symmetry of the high-temperature cuprates. We are now applying this approach to try to determine the symmetry of other superconducting materials suspected to be unconventional, such as the heavy fermion, organic, and ruthenate superconductors. We are also using modifications of the technique to probe details of the pairing state, such as the angular anisotropy of the order parameter magnitude and phase, the dependence of symmetry-induced spontaneous currents on sample geometry, and the onset of subdominant order parameter symmetries at interfaces and defects. © 1999 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

Superconducting quantum interference device (SQUID) interferometry has emerged as the most direct and definitive experimental test of the pairing symmetry of unconventional superconductors [1]. Because of its unique sensitivity to the *phase* anisotropy of the order parameter, rather than to its *magnitude*, this technique is capable of making an unambiguous determination of the symmetry. Applied to the high-temperature cuprates, observations of the phase shift of the order parameter between orthogonal directions by measurements of the SQUID critical current modulation and spontaneous circulating currents have established the predominantly $d_{x^2-y^2}$ symmetry of the superconducting pairing state.

In this paper, we discuss extensions of the SQUID interferometer method for exploring details of the order parameter structure in the cuprates and to materials besides the cuprates that are suspected to exhibit unconventional superconductivity. The phase-sensitive interferometer approach is very powerful and has the potential to resolve many important issues regarding the shape and behavior of the d-wave order parameter and to probe its recently discovered fragility to perturbations. In addition, it is the most promising route to determine the symmetry of other candidate systems such as the heavy fermion, organic, ruthenate, and borocarbide superconductors. However, each of these experiments and materials offers unique challenges that must be overcome. Our intent here is to outline the prospects for applying the SQUID interferometer technique to these problems and to review the status of work in progress in our research program on these issues.

* Fax: +1-217-244-8544; E-mail: dvh@uiuc.edu

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2. Review of the SQUID interferometer technique

The basic configuration of the SQUID interferometer technique is shown in Fig. 1a [2]. The circuit is a dc SQUID consisting of two planar Josephson junctions on the faces of a superconducting crystal, connected by a loop of a second superconductor. The directionality of the pair tunneling enables the order parameter in the *k*-space direction normal to each junction to be probed. Phase coherence around the SQUID loop then results in a response to applied fields that is sensitive to the phase shift inside the superconductor between different tunneling directions. This shows up in the critical current of the SQUID, the circulating currents around the SQUID loop for bias currents below the critical current, and the time-averaged voltage across the SQUID for a bias current above it.

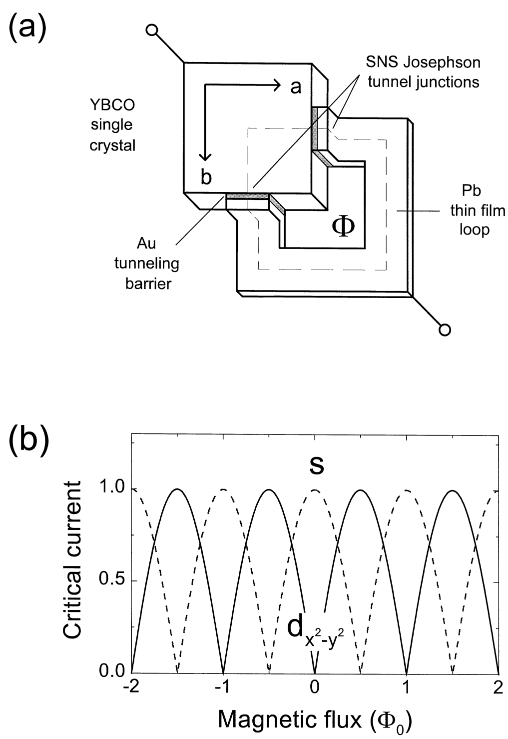

Fig. 1. (a) Configuration of the corner SQUID interferometry experiment in which a dc SQUID is formed by connecting Josephson tunnel junctions on orthogonal faces of superconductor sample with a conventional superconductor loop. (b) Periodic critical current vs. applied magnetic field for the corner SQUID with s and $d_{x^2-y^2}$ order parameter symmetries.

The characteristic property of the superconductor order parameter is its magnitude and phase anisotropy. We define δ to the phase shift between the tunneling directions set by the junction geometries. For an s-wave superconductor, $\delta = 0$ for any pair of junctions because the phase is constant, whereas for a d-wave superconductor, the phase is either 0 or π depending on the location of the tunneling directions compared to the node direction. In the corner SQUID experiments of Wollman et al. [2], the phase shift of π observed ruled out any form of s-wave symmetry and gave strong evidence for the d-wave state. The phase shift in the SQUID configuration is challenging to determine accurately due to the possibility of magnetic flux coupling to the loop from residual background magnetic fields and trapped magnetic vortices in the vicinity of the SQUID loop. Such flux shifts the SQUID critical current modulation pattern and could be misinterpreted as an intrinsic phase shift. By monitoring the reproducibility of the measured phase shift, or by testing the inversion symmetry of the critical current (for both polarities) vs. flux curves, the intrinsic phase shift can be extracted.

An alternate approach is the single junction corner technique, a variation of the corner SQUID experiment [3]. In this scheme, a single Josephson junction straddles a corner in the crystal so that the tunneling is into different directions in the two halves of the junction, as shown in Fig. 2a. For an s-wave superconductor for any junction directions, or for a d-wave superconductor for which both junctions probe the same lobe, the resulting critical current vs. flux pattern is the characteristic Fraunhofer diffraction pattern familiar from single slit optics, $I_c(\Phi) \propto \sin(\pi\Phi/\Phi_0)/(\pi\Phi/\Phi_0)$. However, if the junctions straddle a node so that there is a abrupt jump in the phase across the junction of π at the corner of the junction, the modulation has a distinctly different pattern of the form $\sin^2(\pi\Phi/2\Phi_0)/(\pi\Phi/2\Phi_0)$, as was observed on YBCO crystals. These forms are shown in Fig. 2b. In particular, the critical current is zero for no applied field, reflecting the cancellation of the current in the two sides of the junction. The single junction measurements are substantially less sensitive to both residual magnetic fields and trapped magnetic flux because of the small pickup area; in

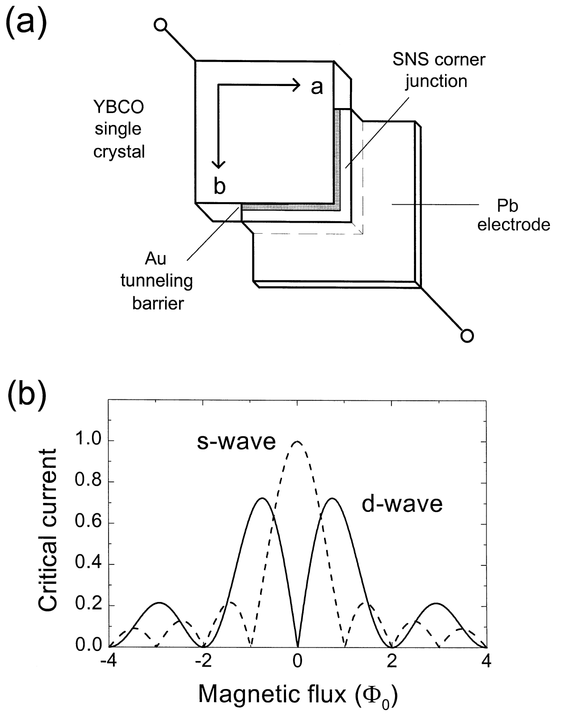

Fig. 2. (a) Modified interferometry experiment using a single corner Josephson junction straddling orthogonal faces of a superconductor sample. (b) Critical current modulation pattern vs. applied magnetic field for the corner junction with s and $d_{x^2-y^2}$ order parameter symmetries.

addition, the presence of trapped vortices is readily identified because they create an asymmetry in the flux modulation curves. For these reasons, the corner single junction experiments have given what is probably the clearest and most unambiguous verification of the d-wave symmetry in the cuprates.

3. Mapping the magnitude and phase anisotropy

The directionality of the tunneling current provides a way to map out the angular dependence of the magnitude and phase of the superconducting order parameter. The *phase* anisotropy can be obtained by fabricating SQUIDs or corner junctions between sample faces at different angles, as in Fig. 3a. For two-dimensional materials such as the cuprates, this is most easily achieved by use of a thin film version of the SQUID interferometer. In this approach, the tunneling directions are defined lithographically and patterned by ion milling of a *c*-axis-oriented film. The two faces are joined with a loop of a conventional superconductor, forming the Josephson junctions. Assuming that one junction is normal to a lobe direction, which for the cuprates is the Cu–O bond direction, Fig. 3b shows the phase shift δ as a function of the angle θ between the junction tunneling directions expected for a d-wave superconductor. Such data have been obtained by Gim et al. [4] but the exact location of the nodes is blurred by trapped flux effects.

A similar technique can be used to gain some information about the *magnitude* anisotropy of the order parameter. In the simplest picture, the critical current of a Josephson junction depends on the product of the order parameters in the two superconductors. For tunneling from an s-wave to a d-wave

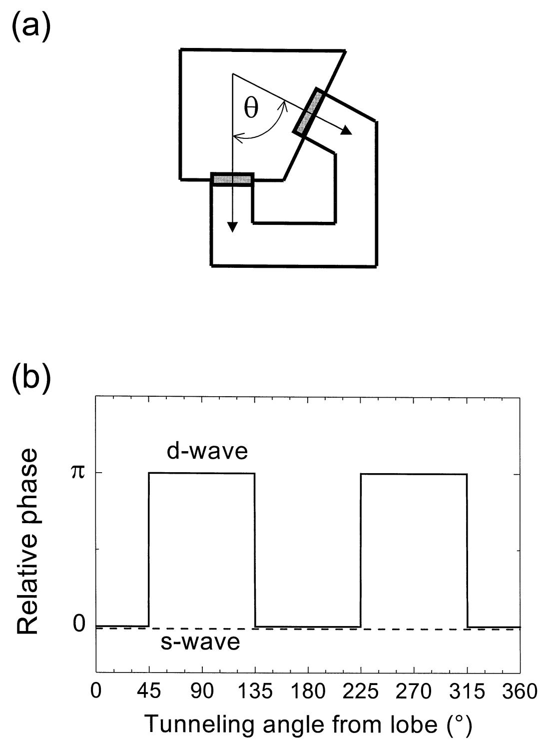

Fig. 3. (a) The SQUID interferometer design for measuring the relative phase of the order parameter in arbitrary *k*-space directions. (b) Expected phase shift as a function of tunneling angle θ. For a d-wave superconductor, the phase shift is either 0 or π, switching discontinuously at the nodes.

superconductor, the dominant factor is the orientation of the order parameter node with respect to the junction normal. The magnitude will be averaged over the tunneling direction cone. The extent of directionality is difficult to estimate, depending on the details of the junction barrier, the current density, and the surface roughness; it is even more difficult to measure since no superconductor with a strong order parameter anisotropy to serve as a reference is known. Typically, it is expected to be on the order of 10°–20°. Fig. 4a shows a YBCO thin film (grown by pulsed laser ablation) patterned into a circle with a series of Nb–Au–YBCO edge junctions at orientations spaced every 7.5°. Fig. 4b plots the measured critical currents vs. angle for the junctions that exhibited a finite critical current in this sample (typically only a fraction of the junctions work, presumably because of the difficulty of ion milling a clean edge in all directions simultaneously). Despite substantial scatter in the results, the angular anisotropy of the critical current is clearly seen, suggesting an anisotropic order parameter. We note that the location of the critical current minimum, expected to be along the node direction, is shifted from this direction by about 20°; further measurements are necessary to determine if this is an intrinsic effect or simply due to a misorientation of the sample film.

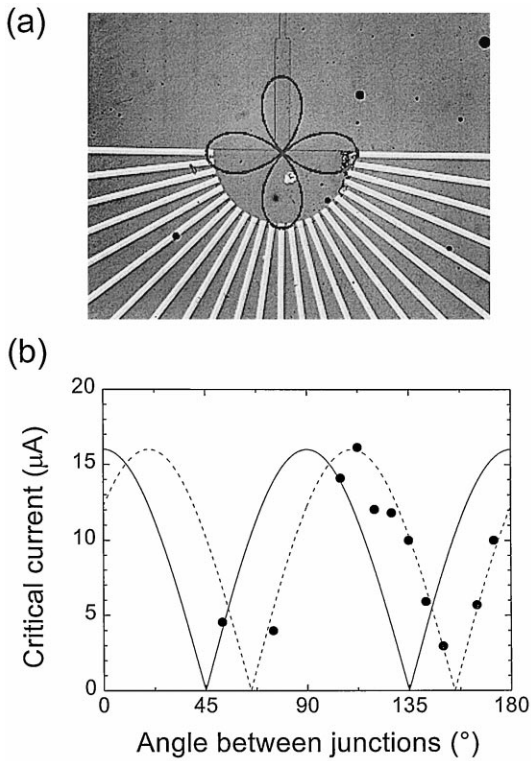

Fig. 4. (a) A series of Josephson junctions spaced every 7.5° on the edge of an oriented-YBCO thin film used to determine the angular anisotropy of the magnitude of the order parameter. Superimposed is the expected order parameter for $d_{x^2-y^2}$ symmetry. (b) Critical current vs. angle for probes exhibiting a finite supercurrent. The solid line shows the expected variation for the $d_{x^2-y^2}$ state; the dashed line is shifted by 20°.

4. Effects of the SQUID geometry

The phase shift in the critical current directly measures the intrinsic order parameter phase shift and it is not expected that the critical current modulation patterns will show any qualitative changes as a function of the SQUID geometry. However, the spontaneous (i.e., in zero field) circulating currents and resulting magnetic flux that are generated in the SQUID to maintain phase coherence around the loop containing an additional phase shift do depend strongly on the geometry. The spontaneous flux has been observed by the Maryland group [5] in the corner SQUID geometry, and by the IBM group [6] in a tricrystal geometry that is equivalent to a three-junction SQUID. In these experiments, the observed flux was close to $(1/2)\Phi_0$, but in general, the magnitude of the flux generated depends on the geometry of the loop and the critical currents of the junctions. This behavior was first discussed by Bulaevskii et al. [7] in connection with a superconducting loop containing a single π-junction. In the corner dc SQUID configuration incorporating a d-wave superconductor, there are no π-junctions but instead, a π-phase shift within the superconductor between different directions. Fig. 5 shows the spontaneous circulating current, the resulting magnetic flux, and the phase drops across the two junctions as a function of the inductance parameter $\beta = 2\pi L I_c / \Phi_0$ for a critical current asymmetry $\alpha = (I_{c1} - I_{c2})/(I_{c1} + I_{c2}) = 0.33$ (i.e., $I_{c1} = 2 I_{c2}$). For small β, it is energetically favorable to flip the phase of the junction with the lower critical current to π (the larger one stays at zero phase drop), paying the price of the increased

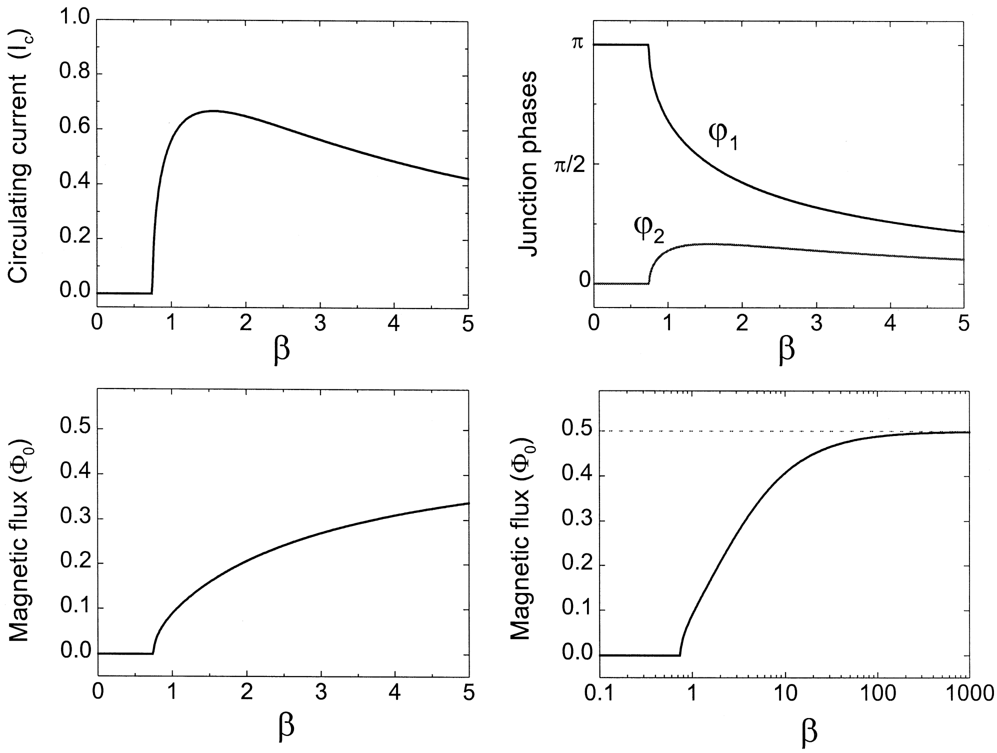

Fig. 5. Spontaneous circulating current, the resulting magnetic flux, and the phase drops across the junctions as a function of the inductance parameter $\beta = 2\pi L I_c / \Phi_0$ for a critical current asymmetry such that $I_{c1} = 2 I_{c2}$. For low β, the phase of one junction is π and no circulating current or flux is required to maintain the phase constraint.

Josephson coupling energy without generation of a spontaneous circulating current. Note that this is not a π-junction, but simply the high energy state of an ordinary Josephson junction whose minimum energy is at zero phase difference. As β is increased, there is an abrupt onset of spontaneous current as the junction phases deviate from 0 and π. At large β, the generated flux approaches $(1/2)\Phi_0$, requiring the current to fall off as $1/\beta$. Thus, the circulating current goes through a peak as β is increased.

Fig. 6a shows our scheme for testing this effect. We have fabricated a thin film version of the corner SQUID in which the loop inductance can be varied in-situ. The SQUID is made by depositing Au and then Nb on the edges of a laser-ablated YBCO thin film patterned by Ar ion-milling. The Nb part of the SQUID loop has a long stripline section whose inductance can be varied by screening with a movable Nb ground plane. In this geometry, the inductance can be changed from approximately 0.1 to 10 μH. For our junctions, which typically have critical currents of 10 μA, this corresponds to a range of β from 0.1 to 10. We couple the flux in the SQUID loop to a dc SQUID detector via a Nb thin film flux transformer. We also have current and voltage leads attached to the SQUID to measure the critical current modulation. Fig. 6b shows the preliminary variation of the SQUID flux as function of the position of the ground plane. In agreement with the theory, we observe a sharp onset in the flux at a particular value of β. Based on our estimates of the loop inductances based on the geometry, we have converted the position to a value of β. The onset value (near $\beta = 5$) is somewhat higher than the projected onset (of order 1), but this value does depend on the junction asymmetry that is difficult to measure independently. At higher β, we observe jumps in the SQUID response, presumably from uncovering trapped magnetic vor-

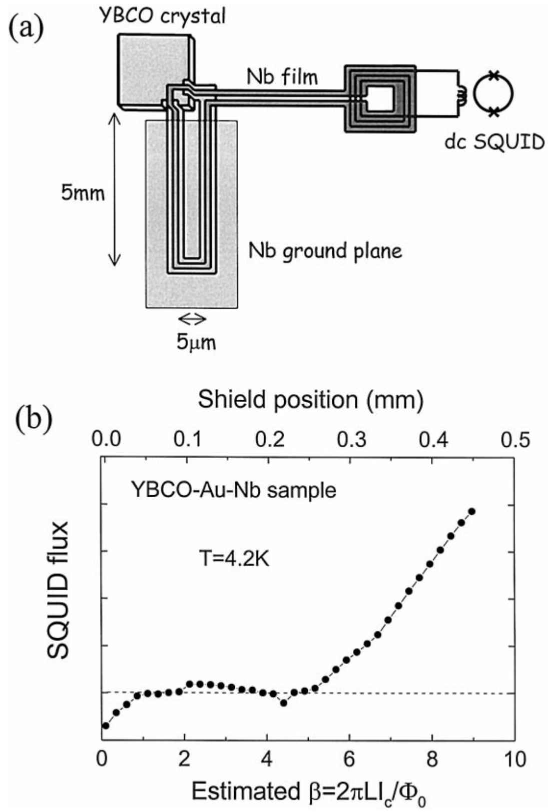

Fig. 6. (a) Variable inductance corner SQUID loop designed to measure the spontaneous flux vs. the inductance parameter β. (b) Preliminary observation of the onset of the SQUID flux as function of the position of the ground plane.

tices in the extended loop as we unscreen it, making it difficult to trace out the full geometry dependence.

The geometry dependence of phase anisotropy-driven spontaneous currents is important for understanding the electronic and magnetic properties of devices and inhomogeneous materials incorporating unconventional superconductors. In particular, it has been suggested that spontaneous currents are responsible for the paramagnetic response observed in granular HTSC composites, the so-called paramagnetic Meissner effect [8,9]. This effect is only seen in some samples, likely due to its dependence on the coupling strength and geometry of the interconnected superconducting grains. Since similar effects have also been observed in conventional superconductors such as Nb, it now seems clear that there are alternative mechanisms.

5. Application to other materials

5.1. Candidates for unconventional superconductivity

After decades of study of superconductivity in which most, if not all, materials considered had conventional s-wave symmetry, there have now emerged many candidates for unconventional symmetry. These materials are characterized by an order parameter that is anisotropic in either magnitude or phase. The principal materials have been extensively reviewed in these proceedings, and include the following.

(1) Cuprates—there is strong evidence from phase-sensitive interferometer experiments, low-temperature penetration depth measurement, and angle-resolved photoemission spectroscopy (ARPES) that the high-temperature cuprate families (YBaCuO, BaSrCaCuO, TlBaCaCuO, HgCaCuO) exhibit $d_{x^2-y^2}$ symmetry; the situation is less clear in the medium-temperature electron-doped NdCeCuO, for which some penetration depth and other measurements suggest s-wave symmetry.

(2) Heavy fermion superconductors—it has long been believed that the heavy fermion superconductors are unconventional, particularly UPt_3 which exhibits two clear phase transitions; however, the actual symmetry has not been established, including even whether the order parameter has even or odd symmetry.

(3) Organic superconductors—evidence is mixed, with some penetration depth measurements indicating s-wave symmetry, but nuclear magnetic resonance (NMR) experiments giving strong indications of a d-wave state; it has been suggested that the order parameter may have a highly asymmetric d-wave order parameter (lobes of one sign much larger than the others).

(4) Ruthenates—there is strong recent evidence that the nearly ferromagnetic Sr_2RuO_4 material (T_c = 1.3 K) has a complex odd (p-wave) order parameter, breaking time-reversal symmetry [10].

(5) Borocarbides—there is no direct indication so far that these materials are unconventional, but they are considered likely candidates because of the strong interplay of magnetism and superconductivity.

In all of these cases, experiments sensitive only to the *magnitude* of the order parameter may suggest, but cannot confirm, the presence of unconventional symmetry. These techniques probe the density of states and/or the number of carriers and the effect of a superconducting energy gap on them. However, impurities can in some cases mimic and in other cases mask these effects, rendering identification of the symmetry risky by this approach. Thus, as with the cuprates, the phase-sensitive interferometer method offers a more direct test of the pairing symmetry in exotic materials.

5.2. Tests for even symmetry states (s, d, g, ...)

For even-symmetry order parameters, the SQUID interferometer approach provides an unambiguous way to determine the symmetry. The key is that the orientation of the junction uniquely determines the tunneling direction (within the tunneling cone). For a real order parameter, this simply means that the junction probes the sign of the order parameter. By fabricating SQUIDs with junctions on different faces of the superconducting crystal, or on different edges of an oriented film, the relative phase anisotropy can be mapped out in either 2D or 3D samples.

The challenge in real materials is to prepare flat surfaces on crystals or films with the desired orientation, and to develop effective processes for making Josephson tunnel contacts to them. In the corner SQUID and junction experiments on YBCO, the first part of this was made easy by the access to single crystals with naturally grown atomically flat faces orthogonal to the *a* and *b* directions. In general, this is not the case, and it is necessary to cut facets on the crystal or film in the desired orientations by artificial means. For crystals, possible approaches include cleaving, spark-cutting, and polishing; for films, edges with controlled orientation can be prepared by microfabrication techniques. In both cases, the primary concerns are the flatness of the face, which controls the directionality of the tunneling, and the quality of the interface, which controls the local superconductor properties.

Preliminary measurements on crystals of κ-(BEDT-TTF)$_2$Cu[N(CN)$_2$]Br (grown by J. Williams at Argonne) exhibit no supercurrents, likely due to degradation of the superconducting surface during fabrication. Strong zero bias anomalies are observed, which could be evidence for a sign change in the superconducting order parameter. Further work is in progress.

5.3. Tests for odd-symmetry states (p, f, ...)

The situation for odd-symmetry order parameter states is considerably more complicated. In this case, there is a sign change for oppositely directed *k*-states. It has been shown that this causes a cancellation of the first-order Josephson effect in the absence of spin–orbit coupling or some other perturbation that breaks the symmetry at the surface [11]. If the second-order Josephson effect dominates, the critical currents are likely to be very (perhaps immeasurably) small. The second-order coupling can be identified by looking at the Shapiro steps in the presence of an applied microwave field, which will be located at voltages $V_n = (hf/4e)n$, twice as closely spaced as for the usual Josephson effect. More likely, any observed supercurrents will be first-order, induced by symmetry-breaking at the surface. In this case, it is not clear which sign of the order parameter will dominate the coupling—this will be determined by details of the superconductor surface, tunneling barrier, and/or local field environment, or may be spontaneously selected during cooling into the superconducting state. As a result, any interferometer experiment that involves coupling of an odd-symmetry superconductor to conventional s-wave superconductor may yield bimodal results in the measured phase shift depending on the sign of the coupling.

Preliminary measurements on crystals of UPt_3 (grown by W.P. Halperin et al. at Northwestern University) have not exhibited supercurrents, despite using a wide range of barriers, counterelectrodes, and junction preparation techniques. As a result, we have been unable to attempt the SQUID interferometer measurements. As noted above, this may be an indication of odd symmetry. However, recently, very small supercurrents have been observed for the first time in UPt_3–Nb junctions, and verified to be of first order [12]. Experiments on these materials are ongoing.

5.4. Tests for time-reversal symmetry breaking

A superconducting state with broken time-reversal symmetry is characterized by a complex supercon-

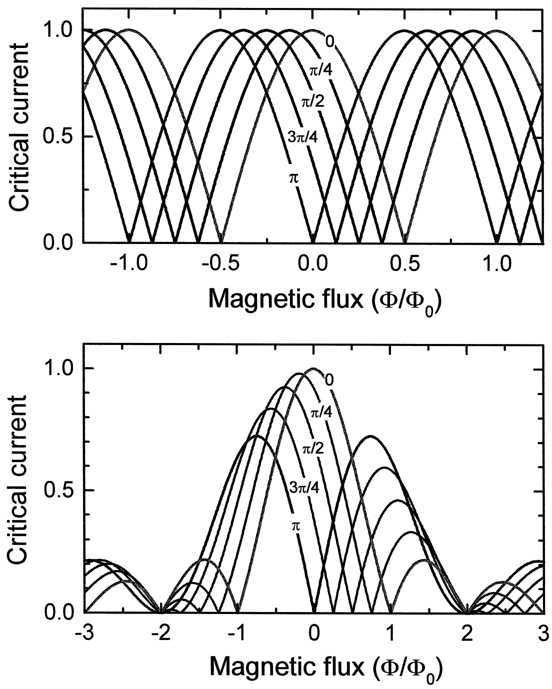

Fig. 7. Critical current modulation pattern expected for different intrinsic phase shifts for (a) SQUID and (b) single junction configurations.

ducting order parameter [13]. This means that the phase shift between different k-space directions can be different from 0 or π. Fig. 7 shows the critical current modulation pattern expected for different phase shifts for the SQUID [14] and single junction configurations. Although either experimental configuration can, in principle, identify the phase shift, the simple shift in the SQUID modulation pattern may be difficult to distinguish from an external flux. In this regard, the single corner junction experiment may be more conclusive in verifying a state of broken time-reversal symmetry.

6. Application to the subdominant order parameters in unconventional superconductors

6.1. Fragility of the d-wave state

Among the most important issues for the implementation of HTSC into electronic applications is the nature of charge transport at interfaces, and the effects of impurities and magnetic vortices on their thermodynamic and electrodynamic behavior. In this regard, perhaps the most exciting and unexpected phenomenon is the fragility of the d-wave symmetry state in the presence of perturbations. There is now a growing theoretical view and some recent experimental indications that the d-wave state dominant in the bulk is readily suppressed at surfaces, at interfaces with other materials, in vortex cores, and in the vicinity of impurities. This suppression allows the emergence of localized regions with different symmetries, likely including complex order parameter states that break time-reversal symmetry. These states are of tremendous scientific interest, promising unique opportunities for studying novel phases in superconductor systems. They may also hold the key to unlocking the mystery of the microscopic pairing mechanism, and will almost certainly impact directly any use of HTSC device in electronic circuits and detectors.

In any anisotropic superconductor, surface scattering modifies the order parameter by coupling and smearing different k-space directions. This effect is particularly pronounced when the order parameter can change sign upon scattering, as in a d-wave superconductor. At a surface or interface, the phase anisotropy leads to a number of unexpected and remarkable results that alter greatly the superconducting properties near the interface and charge transport across it [15,16]. There are three primary effects predicted. (1) The magnitude of the d-wave order parameter is dramatically suppressed at free surfaces and at interfaces with a normal metal or other superconductor. This arises from the pair-breaking effect of Andreev scattering and affects a spatial range of order of the coherence length. For specular reflection, this suppression is strongly anisotropic, yielding a complete suppression along the node direction for which all but normal reflections undergo a sign change, but is absent along the order parameter lobes. (2) Bound quasiparticle states are formed at the surface. Interference between specularly reflected trajectories at the surface that encounter the sign change in the order parameter creates bound states at zero energy [17]. Zero energy bound states enhance the density of states at the Fermi energy, and hence, are reflected as a peak in the zero-bias quasiparticle tunneling conductance. (3)

Under some circumstances, it is predicted that the suppression of the d-wave order parameter can allow the formation of subdominant order parameter phases. Theory indicates that the secondary phases minimize the free energy of the system by maintaining a phase shift with respect to the underlying d-wave order parameter, resulting in a complex superconductor order parameter near the surface that breaks time-reversal symmetry. This has a number of fascinating and testable consequences, including a phase difference between orthogonal directions different from 0 or π, the generation of spontaneous supercurrents, the energy splitting of the zero energy bound states, [18,19] and, at interfaces, spontaneous vortex formation and contributions to the Josephson supercurrent.

6.2. Probing subdominant d-wave superconducting phases by SQUID interferometry

Phase-sensitive tests of the pairing symmetry based on phase coherence in dc SQUIDs and Josephson junctions provide the most direct and definitive probe of the pairing symmetry in the surface region where the bulk d-wave order parameter may be suppressed and give way to subdominant complex order parameter phases. By carrying out interferometer measurements between the (100) and (110) directions in YBCO thin film samples, it should be possible to detect the presence of subdominant surface phases. To do this, it is necessary to fabricate junctions on the edge of the film, using ion mill etching to define the orientation and edge walls. If a surface region with a complex order parameter is formed at the (110)-face, the interferometer will detect a phase shift between 0 and π, depending on the ratio of the $d_{x^2-y^2}$ bulk order parameter and the s or d_{xy} component. This ratio can be studied as a function of temperature, since in general, we expect the subdominant phase to onset at a specific phase transition temperature and to become more pronounced at low temperatures. In the absence of such a state, the SQUID will always yield either a 0 or π phase shift, depending on the location of the node with respect to the junction plane. These experiments are in progress.

6.3. Probing spontaneous surface currents by scanning SQUID microscopy

One of the strongest confirmations of the existence of subdominant surface states with broken time-reversal symmetry would be the direct observation of the spontaneous circulating currents. These are expected to flow within a coherence length of the surface, along with the usual screening currents that extend into the sample by a penetration depth, as shown in Fig. 8a. The spontaneous currents are highly anisotropic. In samples with perfectly flat interfaces along the (100)-directions (along the order parameter lobes), these currents are absent. They are strongest for interfaces along the node direction, creating a region of suppressed order parameter and current flow around the edge of a superconductor island or hole, as indicated in Fig. 8b. We are measuring the magnetic field distribution of high-temperature superconductor islands and perforated films cooled in zero magnetic field using a scanning SQUID microscope (SSM). The goal is to detect the magnetic field generated near the (110)-edge of the sample by the spontaneous surface currents generated. The primary distinguishing features of these currents are their strong dependence on the orienta-

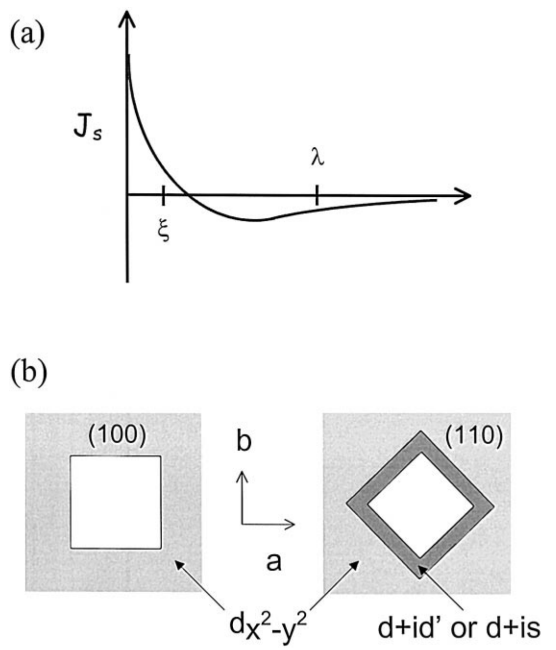

Fig. 8. (a) Variation of currents near an interface supporting a spontaneous surface current. (b) Location of surface currents around (100)- and (110)-oriented holes in a d-wave superconductor.

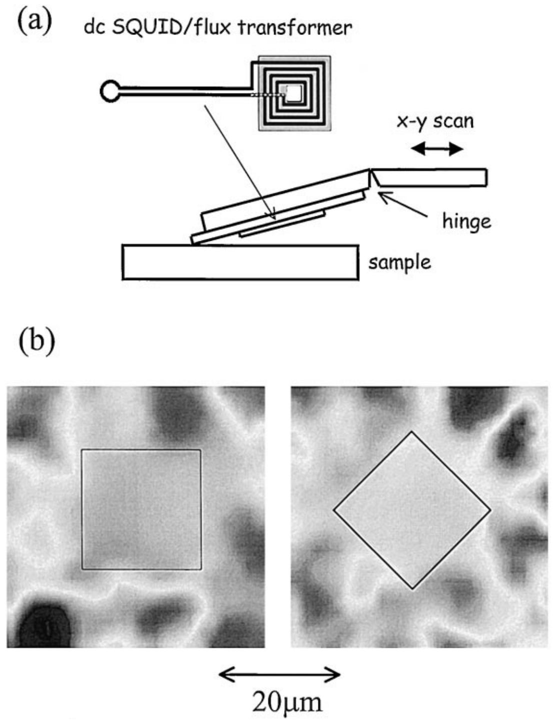

Fig. 9. (a) Design of the SSM. (b) Images of magnetic flux distribution around 20 μm square holes in a YBCO thin film cooled in zero field.

tion of the edges of the islands or holes, and their onset, and, in the absence of flux trapping, reversibility at the transition temperature of the secondary superconducting phase.

The layout of the SSM is shown in Fig. 9a [20,21]. The SSM scans a superconducting pickup loop coupled magnetically to a dc SQUID over the surface of a sample to map out the magnetic field. The SSM uses a detection loop of 10 μm × 10 μm and has a scan range of 1 cm × 1 cm achieved by computer-controlled stepping-motor driven micrometers. The SSM is capable of detecting magnetic fields as small as 10^{-10} T, which corresponds to a flux sensitivity of 10^{-8} Φ_0 in the loop. It is a difficult problem to calculate the magnitude of spontaneous currents and fields near the sample edge. If the currents flow uniformly along the sample edge, the fields should be readily observable.

Fig. 9b shows holes in a YBCO film oriented with edges along the (100) and (110)-directions and cooled in nominally zero magnetic field imaged with the SSM. In both cases, vortices of both polarity are formed at the edge, consistent with spontaneous currents. The principal experimental signatures of the symmetry-induced spontaneous surface currents are the onset at a particular phase transition temperature, and the dependence of the current flow pattern and resulting magnetic field distribution on the orientation of the islands and holes and on the symmetry of the subdominant order parameter that produces it. The expected anisotropy may not be observed due to surface roughness that allows pair-breaking scattering even along the (100)-direction. Further experiments will be needed to verify that these fields arise from secondary phases and are not simply a consequence of trapped magnetic flux.

7. Conclusion

The SQUID interferometer measurements are unique in their ability to probe the phase anisotropy of superconducting order parameters. Although the sample preparation requirements for attaining directional Josephson tunneling into complex superconductor crystals and films are challenging, the ultimate potential for unambiguous determination of the pairing symmetry makes this a worthwhile endeavor. Indeed, as with the cuprates, it may only be through such experiments that a consensus on the symmetry of exotic materials will be reached.

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