**d-wave pairing symmetry in cuprate superconductors**

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Phase-sensitive tests of pairing symmetry have provided strong evidence for predominantly \(d\)-wave pairing symmetry in both the hole- and electron-doped high-\(T_c\) cuprate superconductors. Temperature dependent measurements in \(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}\) (YBCO) indicate that the \(d\)-wave pairing dominates, with little if any imaginary component, at all temperatures from 0.5K through \(T_c\). In this article we review some of this evidence and discuss the implications of the universal \(d\)-wave pairing symmetry in the cuprates.

1. INTRODUCTION

Pairing symmetry in the cuprate superconductors was a subject of intense debate for many years after the discovery of high-temperature superconductivity [1], primarily because the interpretation of many conventional techniques, such as quasiparticle tunneling, NMR, angle-resolved photoemission, and penetration depth measurements, was model-dependent. Nevertheless, these phase-insensitive techniques have produced a large body of evidence for \(d\)-wave pairing in the cuprates. The recent development of phase-sensitive pairing symmetry test [2–7], has yielded compelling evidence for predominantly \(d\)-wave pairing symmetry in a number of optimally doped cuprates [8]. A question naturally arises: How universal is the \(d_{x^2-y^2}\) pairing in cuprate superconductors?

There are numerous theoretical studies suggesting the stability of the \(d\)-wave pair state depends on the details of band structure and the pairing potential [9–11]. There has also been considerable theoretical studies indicating [12–17] that a pure \(d_{x^2-y^2}\) pair state is not stable against the formation of time reversal symmetry breaking states such as \(d_{x^2-y^2} + id_{xy}\) or \(d_{x^2-y^2} + is\), at surfaces, interfaces, near impurities, or below a certain characteristic temperature. On the experimental side, Raman data on \(\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}\) and \(\text{Tl}_2\text{Ba}_2\text{CuO}_{8+\delta}\) systems as a function of oxygen content indicate that the order parameter has \(d\)-wave symmetry near optimal doping and isotropic pairing in the over-doped regime [18]. There are additional indirect experimental evidences for the fragility of the pure \(d\)-wave state [19,20]. The following will examine the universality issues based mainly on the results of phase sensitive pairing symmetry experiments. We will conclude with a brief discussion on implications of \(d\)-wave superconductivity in the cuprates.

2. PHASE-SENSITIVE PAIRING SYMMETRY TESTS

The sign and magnitude of the pair tunneling critical current \(I_c\) across a Josephson junction made with at least one superconductor with unconventional pairing symmetry depends sensitively on the gap function symmetry and relative orientation of the junction electrodes. The ground state of a superconducting loop with an odd number of negative critical currents (termed a “frustrated” or “\(\pi\)” loop) is doubly degenerate and shows spontaneous magnetization of one-half flux quantum (\(\Phi_0/2 = \hbar c/4e = 1.035 \times 10^{-7}\text{G cm}^2\)), provided that \(L \mid I_c \mid \gg \Phi_0\), where \(L\) is the self-inductance of the ring and \(I_c\) is the critical current of the weakest junction in the loop [21–23]. By varying the loop geometry, the presence or absence of the half-integer flux quantum effect can be used for a definitive determination of the pairing symmetry.

The tricrystal pairing symmetry tests use a ring consisting of three crystals with controlled orientation (see Fig. 1) to define the direction of the pair wavefunction. The magnetic flux threading through the tricrystal ring is measured with...
a scanning SQUID microscope for different tricrystal configurations to differentiate between various pairing symmetries. The $\Phi_0/2$ effect is intrinsic in a frustrated geometry, and is observed in ring, disk, and blanket film samples at the tricrystal point.

3. UNIVERSALITY of the $d$-WAVE PAIR STATE

The establishment of $d$-wave pairing in some of the cuprates has imposed well defined constraints on possible models of high-temperature superconductivity, but it does not specify the high-$T_c$ mechanism. To gain further insight into the origin of high-temperature superconductivity, it is important to determine whether the $d_{x^2-y^2}$ pairing symmetry is universal. One can investigate the universality issues from the following aspects.

3.1. Various cuprate systems

Phase-sensitive SQUID interferometry, tricrystal magnetometry, SQUID magnetometry, and single junction interferometry experiments have demonstrated $d$-wave pairing symmetry in YBCO single crystals or $c$-axis oriented epitaxial films. In addition, tricrystal magnetometry experiments have demonstrated $d$-wave pairing symmetry in various high-$T_c$ hole-doped cuprate systems such as $T_{12}Ba_2CuO_{6+\delta}$, $GdBa_2Cu_3O_{7-\delta}$, and $Bi_2Sr_2CaCu_2O_{8+\delta}$. (For a more complete tabulation of the phase-sensitive experiments see Ref. 8). More recently, the pairing symmetry of the electron-doped cuprate superconductors $Nd_{1.85}Ce_{0.15}CuO_4-\delta$ (NCCO) and $Pr_{1.85}Ce_{0.15}CuO_4-\delta$ (PCCO) has been determined to also be predominantly $d$-wave by observing the half-flux quantum effect in $c$-axis thick blanket films ($\sim1\mu m$ thick) epitaxially grown on tricrystal substrates with the configuration of Fig. 1. Samples with two other geometries, designed to be unfrustrated for a $d$-wave superconductor, do not show the half-flux quantum effect. Shown in Fig. 2a is a scanning SQUID microscope image of a NCCO film deposited on a frustrated tricrystal STO substrate, cooled to 4.2K in nominal zero field. This image was obtained by subtracting an image with an external magnetic field.
nally applied field of -0.15mG, which stabilized the half-quantum magnetic vortex with the flux pointing down, from an image taken with an applied field of 0.15mG, resulting in a half-quantum magnetic vortex pointing up, and dividing by 2. This results in an image of the half-quantum magnetic vortex with effects from surface roughness, a smoothly varying magnetic background, and the mutual inductance between the SQUID and sample subtracted out. Figure 2b shows fitting of cross-sections through the data of Fig. 2a to expressions for the magnetic signals expected from a Josephson vortex centered at the tricrystal point, with a total flux of $\Phi_0/2$ [28]. The height $z$ of the pickup loop was determined by fitting a bulk Abrikosov vortex. The solid lines in Fig. 2b are fits to cross-sectional data for the horizontal and diagonal grain boundaries, assuming a total flux of $\Phi_0/2$ for this vortex, using the Josephson penetration depths $\lambda_f$ for the two grain boundaries as the sole fitting parameters. The dashed lines, assuming a flux of $\Phi_0$, are much worse fits. These results indicate that the electron-doped superconductors, just as the hole-doped superconductors, have $d$-wave pairing symmetry.

3.2. Temperature dependence of $\Phi_0/2$

It is of interest to find out whether $d$-wave pairing will change to $s$-wave, for example, as a function of temperature. However, the phase-sensitive experiments described above were all performed at liquid helium temperature. With a recently developed variable sample temperature scanning SQUID microscope [27], the temperature dependence of the half-integer flux quantum effect in tricrystal YBCO was studied. It was found that the total flux of the Josephson vortex at the tricrystal point remains constant (i.e. $\Phi_0/2$) from 0.5K through $T_c$ (~90K) [28]. This finding means that the $d$-wave pair state dominates at all temperatures below $T_c$, and that there is little, if any, time-reversal symmetry breaking component in the order parameter, over the entire temperature range. This is consistent with earlier studies, which found less than a few percent of time-reversal symmetry breaking component in phase-sensitive measurements at low temperatures [29].

3.3. The effect of doping

Is there any band structure (doping) effect on pairing symmetry? In the competition between $s$-wave and $d$-wave channels for high-temperature superconductivity, is there any factor that can stabilize the $d$-wave pairing? In the literature, there have been some theoretical studies dealing with these issues: for example, based on a next-nearest-neighbor pairing interaction, the symmetry of a BCS condensate is predicted to vary as a function of energy band filling and other band parameters [9–11]. The $d$-wave pairing channel is energetically favored in a wide range of doping centered around half-filling. The stability of the $d$-wave pair state may be enhanced by the proximity of the Fermi level to the van Hove singularity in the 2D bands of the CuO$_2$ plane [30]. A series of phase-sensitive pairing symmetry tests as a function of doping in a model system such as Tl$_2$Ba$_2$CuO$_{6+\delta}$, HgBa$_2$CuO$_{4+\delta}$, Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$, or Y$_{1-x}$Ca$_x$Ba$_2$Cu$_3$O$_{7-\delta}$ could test for these effects.

4. CONCLUDING REMARKS

Phase-sensitive experiments have produced strong evidence for predominantly $d$-wave pairing symmetry in hole- and electron-doped cuprate superconductors. These tests also indicate, within the experimental accuracy (~3% at low temperatures), the absence of pairing with broken time-reversal symmetry. The universality of $d$-wave pairing symmetry in bulk high-temperature superconductors is thus well-established. The possibility of pair states without time-reversal symmetry invariance (e.g. $d_{x^2-y^2}+id_{xy}$ or $d_{x^2-y^2}+is$) induced at surfaces, interfaces, or around impurities or defects is being actively investigated (see Ref. 5 and references therein). Recent observations of a splitting of the zero-bias conductance peak in quasiparticle tunneling [31] and spontaneous magnetization in c-axis YBCO thin films [32,33] represent possible evidence for such pair states.

Dominant $d$-wave pairing symmetry in both the hole- and electron-doped cuprates is expected from single-band models of the CuO$_2$ planes, in which the electron-hole symmetry is an intrin-
sic property (see e.g. Poole et al. 22). From another perspective, the predominance of $d_{x^2-y^2}$ pairing in cuprates underscores the important role of strong electron correlation in determining the superconducting gap symmetry and other properties. It is experimentally and theoretically well established that a strong on-site Coulomb repulsion is present in all cuprates. Such a strong electron correlation causes the universally-seen Mott transition at half-filling. The strong on-site Coulomb repulsion rules out simple $s$-wave pairing.

In future, a systematic study of pairing symmetry as a function of doping, impurities, ... is important for a better understanding of high-temperature superconductivity.

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