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Experimental detection of sign-reversal pairing in iron-based superconductors

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We propose a modified Josephson corner-junction experiment which can test whether the order parameter in the iron pnictides changes sign between the electron and hole pockets of the Fermi surface.

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Iron pnictides represent the newest member of the class of correlated materials in which superconductivity (SC) emerges from doping an ordered state.[1,2] One of the intriguing proposals for superconductivity in these mutiband systems is that spin fluctuations mediate electron pairing between different regions of the Fermi surface but with different signs for the order parameter.[3] In the unfolded Brillouin zone, the regions of the Fermi surface which are relevant are the electron and hole pockets located at the M and Γ points,[4] respectively, as illustrated in Fig. 1(a). The result is a nodeless gap, denoted as $s_\pm$, with a rough momentum dependence of $\cos k_x \cos k_y$.[3] While the preponderance of the experiments supports isotropic nodeless superconductivity[4–6] in both the 1111 and 122 materials, the power-law behavior of the spin-lattice relaxation rate $T_1^{-1} \approx T^3$ has been used as a strong indication of line nodes.[7] However, nodeless $s_\pm$ pairing has recently been shown to also yield T^3 behavior at high temperatures.[8] Fine tuning with disorder is necessary to obtain the T^3 dependence of $1/T_1$ at low temperatures. Alternatively, superconductivity with multiple gaps can also give rise to such a deviation from the standard Bardeen-Cooper-Schrieffer (BCS) exponential falloff of T_1^{-1}. In fact, superconductivity in $Ba_{0.6}K_{0.4}Fe_2As_2$ and $PrFeAsO_{0.89}F_{0.11}$ is consistent with at least two gaps with ratios of 2 and 3.2, respectively. Hence, the complete consistency of $s_\pm$ pairing with the experimental data is far from settled.

Nonetheless, given the novelty of the $s_\pm$ state, it is important to definitively determine its relevance to the pnictides. Although there are some proposals on phase-sensitive measurements such as a three layer sandwich structure,[9] they are not direct probes of the order parameter phase. As phase-sensitive measurements[10] using Josephson interferometry were pivotal in settling the question of the symmetry of the order parameter in the cuprates, we focus here on whether or not such a similar experiment can be performed to falsify the claim that the order parameter in the pnictides has $s_\pm$ symmetry. Detecting an $s_\pm$ state in the pnictides poses a distinct challenge from discerning the sign change in the $d_{x^2-y^2}$ state in the cuprates because the sign change occurs along the crystal axes.[10]

Central to the design of any standard superconductor-insulator-superconductor (SIS) junction oxide barrier is the highly directional nature of the transport. Namely, the junction can only detect the order parameter in the direction perpendicular to the crystal face.[10] It is for this reason that a standard corner junction can be used to detect the sign change of the $d_{x^2-y^2}$ order parameter because the order parameter has a natural alignment along the crystal axes. In this sense, detecting the $s_\pm$ state depicted in Fig. 1(b) poses a distinct challenge because no such alignment of the order parameter and the crystal axes is present. Consider an $s_\pm$ SC and a conventional s-wave SC joined by a weak link. Let Δ_0 and Δ_1 be the magnitude of the order parameters at the M and Γ points, respectively, in the iron-based superconductor. The superconducting quantum interference device (SQUID) design is shown in Fig. 1(b). Let us consider the gap on the M pocket which experimentally is less than $\Delta_1 = 25$ meV.[11] A gap of this magnitude corresponds to a wave vector for the center of mass of a Cooper pair emanating from the M pocket that is less than $K_c = m_{\text{eff}} \Delta_1 / \hbar p_F \approx \frac{0.026}{k_F} (\frac{m_{\text{eff}}}{m_e}) (\frac{\pi}{a_0})^2$, where m_{eff}, m_{e}, $a_0 \approx 2.83$ Å, p_F, and k_F are the effective mass, electron mass, lattice constant, Fermi momentum, and Fermi wave vector, respectively. This number is much smaller than the wave vector $Q = (\pi, \pi)/a_0$, in the folded Brillouin Zone, by a factor of 3 at least. In this case, regardless of the direction of the Cooper pairs, it is impossible to choose the wave vector $\mathbf{K}_c$ of a Cooper pair emanating from M so that the net wave vector $\mathbf{K}_{\text{net}}$ is perpendicular to the C or D faces of the junction in Fig. 1(b). However, this condition is easily met at face E which lies at an angle of 45° from the horizontal. Such scattering of a Cooper pair from Γ to M points requires Umklapp scattering as the net momentum transfer is $\mathbf{Q}$. By contrast, the order parameter associated with Γ pocket in the folded zone can be sensed by all faces. Taking this into account, we compute the associated critical current for a SQUID joining surfaces C and D, D and D, or D and E. For the former two, the critical current is given by

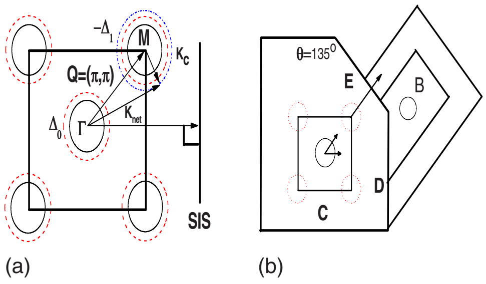

FIG. 1. (Color online) Design of the SQUID junction to test $s_\pm$-wave superconductivity. (a) Fermi surface in the folded Brillouin zone to show the principle of design. (b) The SQUID design. The left-hand side of the junction is an iron-based SC which is cut on the [010] (E face), [110] (D face), and [1$\bar{1}$0] (C face) planes. Any two of the planes are connected to a conventional s-wave SC on the right-hand side through standard oxide-barrier SIS junctions (Ref. 10). The magnetic field is perpendicular to the plane.

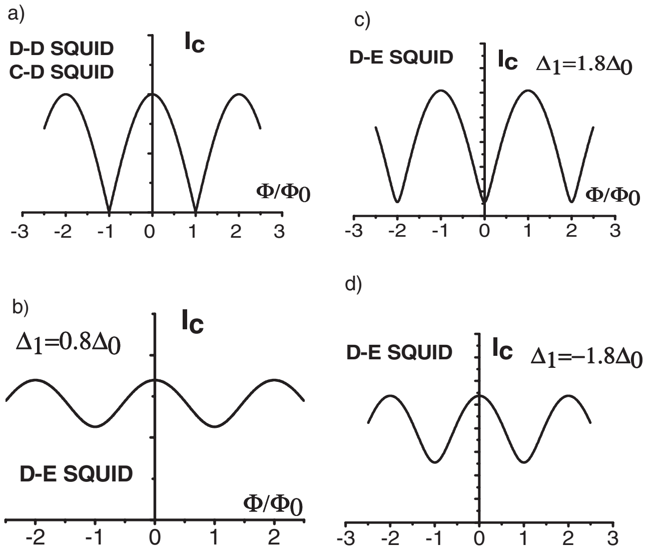

FIG. 2. All possible interference pattern for different x values where x is defined as $\Delta_1=-x\Delta_0$. (a) For junction connecting *D-D* or *C-D* faces; (b)–(d) are all junction connecting *D-E* faces. (b) $x \in [0,1]$; (c) $x \in [1,\infty)$; and (d) $x \in (-\infty,0]$.

$2\Delta_0 \sin(\Phi/\Phi_0)$ where Φ, Φ_0 is the magnetic flux and flux quantum. This is the standard s-wave result. However, for a *D-E* SQUID, the situation is different; the critical current,

$$\sqrt{\Delta_0^2+(\Delta_0-\Delta_1)^2+2\Delta_0(\Delta_0-\Delta_1)\cos(\Phi/\Phi_0)}, \tag{1}$$

is governed by the magnitude and sign of the order parameter at the M and Γ points as depicted in Fig. 2. To recover the standard s-wave result simply requires reversing the sign of Δ_1. All the possible interference patterns as a function of Φ/Φ_0 are shown in Fig. 2. For the 1111 pnictide material, there are two hole pockets at the Γ point with $\Delta_0=(6+12)$ meV and two electron pockets at M point with $\Delta_1=(12+12)$ meV. This case corresponds to Fig. 2(c).[11] As all the possible interference patterns differ substantially from the standard s-wave result, this experimental design should offer a definitive test of $s_\pm$ pairing in the pnictides.

Note added. After this paper was completed, a similar idea was proposed by Mazin and Park (Ref. 12). We offer here a more complete explanation of why along the D face only holes contribute the current, while along the E face both electrons and holes do. Further, *D-E* has a π phase shift only when the gap on electron Fermi surface is larger than the gap on hole Fermi surface which is not mentioned in Ref. 12.

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