PHYSICS

# Sign Flips and Spin Fluctuations in Iron High-$T_c$ Superconductors

The symmetry of electron-pairing interactions in iron-based superconductors suggests a shared spin-mediated pairing mechanism with the cuprate family.

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In superconductors, the key process that allows current to travel without resistance is the formation of electron pairs that move as a single quantum state. The mechanism of pairing in the high-temperature (high-$T_c$) cuprate superconductors is still elusive, so the recent discovery of iron-based superconductors (*1*) sparked the hope that comparison with the cuprates would lead to a better understanding of pairing in both materials. On page 474 of this issue, Hanaguri *et al*. (*2*) report the experimental determination of the pairing symmetry in $FeSe_xTe_{1-x}$. Combined with the recent observation of a spin fluctuation resonance in this material (*3*) akin to that seen in the cuprates (*4*), a compelling hypothesis emerges that these high-$T_c$ superconductors share a common pairing mechanism.

Pairing in both conventional and high-$T_c$ superconductors must overcome the large repulsive force between two like charges. In conventional superconductors, pairing arises from a normal metallic state, where electrons are numerous and move freely to screen any local inhomogeneity. One electron plus all of the screening electrons act like a single "quasiparticle." Despite the strong repulsion that should arise between any two isolated electrons, even a small attractive interaction such as a phonon—a wake of displaced ions—causes the pairing of quasiparticles. In conventional superconductors, phonon mediated pairing is typically isotropic, with spherical or "*s*-wave" symmetry.

In high-$T_c$ cuprates, the story is more complicated because their "normal" state has too few charge carriers to screen effectively. Electrons interact quite strongly, allowing

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new pairing possibilities. Passionate voices have argued for several candidates, including phonons, exotic charge excitations, or a spin-mediated repulsive potential. This latter mechanism can pair two quasiparticles only if their wave functions have opposite sign (*5*). To decide between competing models, experiments must measure the symmetry of the order parameter: the dependence of both the amplitude and quantum-mechanical phase of the pairing potential on quasiparticle momenta.

In the cuprates, it took almost a decade to establish that the pairing symmetry is "*d*-wave" (*6*). Angle-resolved photoemission spectroscopy (ARPES) revealed four directions of quasiparticle momentum in which the pairing amplitude is zero; these are called nodes in the order parameter (see the figure, panels A and C). Quantum tunneling experiments in a corner junction geometry established that the phase changes sign between the four nonzero lobes of the order parameter (see the figure, panel E).

Insights into the pairing symmetry of the iron-based superconductors came much sooner after their discovery. Calculations by Mazin *et al.* (*7*) showed that five energy bands—plots of electron energy as a function of momentum—cross the Fermi level that separates the occupied from unoccupied electronic states (see the figure, panels B and D). These crossings, or Fermi surfaces, exhibit a "nested" structure. They have roughly the same shape but are offset from each other by a momentum that corresponds to antiferromagnetic spin fluctuations. Mazin *et al.* concluded that spin-mediated interband pairing is energetically favorable if the order parameter changes sign between the nested Fermi surfaces (*7*). Each band is individually isotropic—an *s*-wave has only one lobe and does not have a well-defined sign in isolation—but if there are several *s* bands, each can be assigned a different sign.

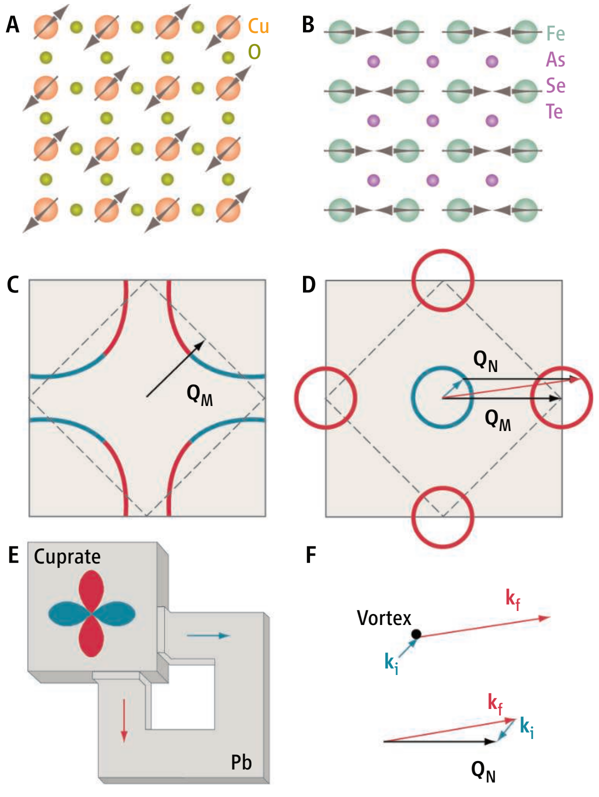
This "*s*±" pairing-symmetry model, the strongest candidate of the many that had been proposed, was hard to verify experimentally. Unlike the *d*-wave case, the phase change occurs not between two different momentum directions, but between two different magnitudes of quasiparticle momentum that may lie along the same direction. Macroscopic geometrical separation of the two phases, as in the cuprate corner-junction experiment, is not possible.

ARPES studies showed no nodes but could not determine phase in $NdFeAsO_{1-x}F_x$, a so-called "1111" FeAs superconductor (*8*). A detection of half-quantum magnetic flux in a loop between $NdFeAsO_{1-x}F_x$ and conventional superconducting niobium showed a phase change in the order parameter (*9*). Combining these two experiments proved the *s*± symmetry in this material, but not the pairing mechanism. A neutron scattering experiment on a related "122" FeAs superconductor, $Ba_{0.6}K_{0.4}Fe_2As_2$, detected a resonant spin fluctuation that arose only in the superconducting state, at exactly the nesting wave vector to take advantage of the *s*± symmetry (*10*) (see the figure, panels B and D).

However, the universality of these results for high-$T_c$ iron-based superconductors has been questioned. Another family of iron materials, showing superconductivity up to 14 K (37 K under pressure), is based not on arsenic but on sulfur, selenium, and tellurium (*11*). The band structure in $FeSe_xTe_{1-x}$ appeared similar (*12*), but neutron scattering showed that the dominant static magnetic order in the parent FeTe compound is not the nesting wave vector (*13*). Combined with the absence of a spin-density-wave gap (*12*), these results fueled speculation that the superconducting mechanism was entirely different in the two families.

Further exploration of $FeSe_xTe_{1-x}$ uncovered more similarities. A spin resonance occurring at the expected nesting vector turns on just as the material enters the superconducting state (*3*). Half of the pairing mechanism—the existence of the spin mediation—was now in place, but did the Fermi surfaces in $FeSe_xTe_{1-x}$ have appropriate signs to allow pairing?

Studies of pairing symmetry must measure momentum, so Hanaguri *et al.*'s use of scanning tunneling microscopy (STM), which measures the positions of electronic states with atomic resolution, seems an unlikely choice. However, STM has provided a wealth of momentum information on the cuprates from quasiparticle interference imaging (*14*). Several types of disorder in a material can elastically scatter a quasiparticle, changing its momentum but not its energy. The initial and final quasiparticle states interfere and create a ripple in the density of states whose period is set by the difference in their momenta (see the figure, panel F) Not only can the momenta of the original, unscattered quasiparticle states be deduced, but the amplitudes of these ripples can reveal




**Spin fluctuations and symmetry.** Common features can be found in the spin fluctuations and pairing symmetry in cuprate and iron-based superconductors. (**A** and **B**) Atomic lattices in the relevant planes of (A) cuprate and (B) iron-based superconductors. Arrows depict the spin resonance associated with superconductivity in these compounds. These spin patterns are not static but fluctuate. (**C** and **D**) Fermi surfaces as a function of electron momentum illustrate pairing symmetries. The large squares (solid gray lines) denote the Brillouin zones (unit cells in momentum space) containing a single atom of (C) copper or (D) iron. The Fermi surfaces are denoted in blue (positive phase) and red (negative phase); for (C), the nodes (zero amplitude) occur where the blue and red arcs touch. The spin fluctuations in (A) and (B) are described by wave vectors $\mathbf{Q}_M$. (**E** and **F**) Phase-sensitive tests of the pairing symmetry. (E) In cuprates, quasiparticles of each phase can be separated by the macroscopic geometry of the corner junction shown. When the currents, shown by arrows, recombine, changes in their interference with applied magnetic field reveal that they exited the cuprate with opposite phase (*16*). (F) In the iron-based materials, the two phases cannot be separated by their direction, so a microscopic measurement is required to obtain phase-sensitive information. Hanaguri *et al.* used a scanning tunneling microscope to image interference effects created by magnetic vortices. Increasing interference between incoming and outgoing quasiparticles, with wave vectors $\mathbf{k}_i$ and $\mathbf{k}_f$, from the two different Fermi surfaces, shows that the phase changed sign. The difference wave vector, $\mathbf{Q}_N$, matches the spin fluctuation wave vector $\mathbf{Q}_M$ recently detected (*3*).

the phase difference between incoming and outgoing quasiparticle waves.

Hanaguri *et al*. applied a magnetic field to introduce a new type of sign-changing scattering center, a superconducting magnetic vortex. As the magnetic field was increased, the quasiparticle scattering was increasingly dominated by these vortices. An increase in the amplitude of interference between quasiparticles from the two different Fermi surfaces was seen relative to interference between quasiparticles from the same Fermi surface, showing that the two different Fermi surfaces must have opposite sign.

High-$T_c$ superconductor research has focused both on fundamental understanding and on practical applications. Thus, it is ironic that the magnetic vortices used to better understand high-$T_c$ superconductivity are also the primary impediment to applications due to their unwanted dissipative motion when current is applied. So far, the vortices appear to be well-pinned in iron-based superconductors (*15*), but $T_c$ has maxed out at 57 K. However, the recent evidence (*2*, *3*) establishing the spin-mediation as a leading candidate for the pairing mechanism that operates across the major families of high-$T_c$ iron-based superconductors also provides insight into the mechanism of cuprate superconductivity. This result also suggests a promising avenue in the search for higher $T_c$ materials—look for materials with similar band structures that undergo magnetic interactions (*5*).

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