Superconductivity

https://doi.org/10.1038/s41567-023-02375-y

Pocket pairs in iron-based materials

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Experiments with unprecedented energy and momentum resolution reveal the nature of the pairing symmetry in KFe_2As_2 and pave the way for a unified theoretical description of unconventional superconductivity in iron-based materials.

Any description of the microscopic mechanisms responsible for superconductivity requires knowledge of the pairing symmetry, which describes how electrons at the Fermi surface couple to one another in momentum space. In iron-based superconductors with a Fermi surface consisting solely of hole pockets, the nature of the pairing symmetry remains unsettled. Writing in *Nature Physics*, Dingsong Wu and colleagues report a distinctive spectroscopic determination of the pairing symmetry in a prototypical iron-based superconductor with only hole pockets[1]. Their state-of-the-art experiments revealed a pairing symmetry closely related to that of most Fe-based materials, where the Fermi surface consists of both hole and electron pockets. Their findings represent an important step towards reaching a unified theoretical description of iron-based superconductors.

When the temperature is lowered below a critical temperature, superconducting materials undergo a second-order phase transition and enter a superconducting state. One of their defining traits is the sustainability of supercurrents — electric currents flowing with zero resistance. The supercurrents originate from the collective, coherent motion of the Cooper pairs, bosonic entities consisting of two paired electrons. The Cooper pairs condense into the ground state, and their density defines the order parameter of the superconducting transition[2].

In the superconducting state, the one-particle excitation spectrum has a gap near the Fermi level. Since the gap is proportional to the order parameter, knowledge of it is fundamental for the description of a superconducting transition.

The challenge facing any microscopic theory of superconductivity is the description of Cooper pair formation: how can electrons avoid repelling one another and form a bound state? The first successful microscopic theory by Bardeen, Cooper, and Schrieffer describes the pairing as originating from an effective attraction between electrons mediated by phonons[3]. In this conventional case, the gap is essentially isotropic over the whole Fermi surface, with a symmetry referred to as *s*-wave[2]. When pairing is not phonon-mediated, superconductivity is termed unconventional. In this case the pairing symmetry acquires particular importance. When the interaction between electrons is repulsive, the pairing symmetry is constrained to ensure a sign change of the gap found in different locations on the Fermi surface[2].

Many iron-based superconductors have Fermi surfaces consisting of different sheets formed by energy bands of different character, with hole and electron pockets at the zone centre and corners, respectively. In this case the gap can be *s*-wave on each sheet, but its sign must change between the hole and electron pockets, a symmetry denoted by $s_{\pm}$ (ref. 4). When the Fermi surface is composed of only hole pockets, however, the determination of the pairing symmetry is controversial. Wu and colleagues were able to take a significant step forward in this endeavour by studying the pairing symmetry in KFe_2As_2 with angle-resolved photoemission spectroscopy (ARPES) experiments.

KFe_2As_2 has a complicated Fermi surface consisting of only hole pockets originating from different bands. Wu and colleagues measured the magnitude of the gap over the entire Fermi surface and found that it can be either isotropic or very anisotropic, depending on which sheet it is extracted from. The superconducting gap is a complex function of electron momenta and spins, and its phase describes its symmetry. ARPES experiments alone cannot detect the phase of the gap function.

Nevertheless, the extreme precision of the measurements allowed for the identification of two vectors that connect portions of the Fermi surface with the two spin-resonance wave vectors found in the superconducting state with neutron scattering experiments[5]. Since the spin resonance mode is a signature of the gap sign change, this identification indicated that the portions of the Fermi surface at the centre and the corner of the Brillouin zone have a reversed sign of the superconducting gap. This allowed the authors to propose that the pairing symmetry is $s_{\pm}$, with the sign reversal between the centre and corner points. Moreover, the authors discussed how their findings are consistent with the observation of spin fluctuations in neutron scattering, ultimately suggesting that spin fluctuations are the pairing mechanism.

The determination of the Fermi surface and the gap structure required extensive measurements taken in different experimental conditions. What made the experiments extremely challenging was the fact that KFe_2As_2 has a low critical temperature of about 3.5 K, a very small gap size below 1 meV, and a complicated Fermi surface originating from many bands. Consequently, the experiments had to be carried out at extremely low temperatures, and with high energy and momentum resolution. The use of low energy photons delivered by a laser was pivotal in fulfilling these requirements, but posed an additional challenge as it was impossible to directly measure the corner pockets. It was possible, however, to measure their replicas in the vicinity of the centre point, where the bulk bands were folded back to because of the presence of a surface reconstruction.

Wu and colleagues carried out a series of painstaking experiments to ensure as best they could that the gap measured on the Femi surface replica was indeed representative of the bulk gap structure at the zone corner. The accomplishment of measuring the gap over the whole FS in KFe_2As_2 with unprecedented precision is a compelling novelty of this work. It also represents a crucial step in the development of advanced experimental protocols that enable the provision of the highest-quality data.

The study of Fe-based superconductors provides an opportunity to understand important aspects of unconventional superconductivity, chief among these being its interplay with magnetism. Systems hosting only hole or only electron pockets present a challenge since they appear to defy the $s_{\pm}$ pairing that describes systems that host both types of pockets. Time and further scrutiny will tell whether these findings bring unity to the field, but certainly the present work will contribute substantially to the open debate as to what extent the $s_{\pm}$ pairing is applicable to the iron-based superconductors.

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Published online: 25 January 2024

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Competing interests

The author declares no competing interests.