HEAVY-FERMION SUPERCONDUCTIVITY

How the heaviest electrons pair up

Scanning tunnelling spectroscopy in a heavy-fermion superconductor provides direct access to the anisotropy of the pairing gap, opening a window for investigating the nature of the pairing interaction.

Louis Taillefer

Unconventional superconductors, in which electrons rely only on themselves and not on phonons to form Cooper pairs, hold the record for superconductivity at the highest critical temperature T_c. In copper oxides called cuprates T_c can be as high as 164 K — half way to room temperature. The big question is what interaction causes such unconventional pairing, and how might it be enhanced. In a family of materials known as heavy-fermion metals — compounds with 4*f* or 5*f* electrons, typically from Ce or U atoms — the interaction is thought to be mediated by the spin fluctuations of a nearby antiferromagnetic phase[1]. To understand how this works, a key piece of information required is the symmetry of the pairing state[2]. In *Nature Physics*, Milan Allan *et al.*[3] and Brian Zhou *et al.*[4] report the first scanning tunnelling spectroscopy (STS) studies of a heavy-fermion superconductor. Their measurements on $CeCoIn_5$ show that the anisotropy of the pairing gap is consistent with the *d*-wave symmetry of the cuprates (Fig. 1).

The power of the STS technique is its ability to map the real-space variations in the local electronic density of states with atomic resolution, and an energy resolution good enough to access the small pairing gap of $CeCoIn_5$. The operating temperature must be well below $T_c = 2.3$ K, requiring the use of a dilution refrigerator, ideally with a magnet that can apply a magnetic field beyond the critical field $H_{c2} = 5.3$ T. These are demanding experiments.

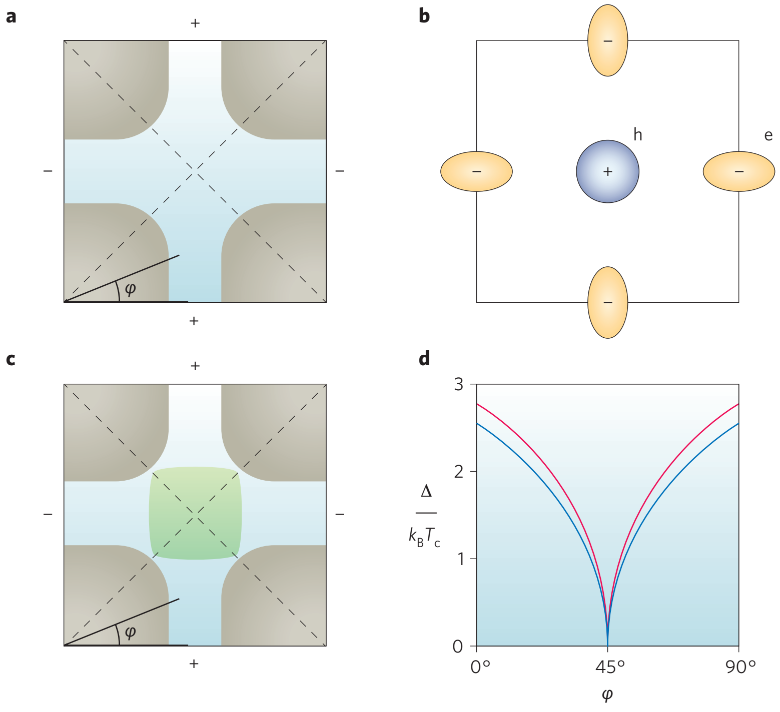

Figure 1 | Fermi surfaces and superconducting gap anisotropy. **a**, Fermi surface of a typical cuprate, made of a single hole-like cylinder. The superconducting state has d_{x2-y2} symmetry, and thus changes sign upon crossing the zone diagonals. This produces zeros (or nodes) in the gap. **b**, Fermi surface of a typical iron pnictide superconductor, consisting of a hole-like pocket at the zone centre and an electron-like pocket at the zone boundary. The gap changes sign from one to the other, but there are no nodes. The symmetry is *s*-wave. **c**, The Fermi surface of $CeCoIn_5$, showing two of the sheets in the tetragonal basal plane. The gap anisotropy detected by Allan *et al.* and Zhou *et al.* on one of the Fermi surface sheets is at its minimum along the diagonals, and is therefore consistent with d_{x2-y2} symmetry. **d**, Angle dependence of the superconducting gap magnitude in the cuprate Bi-2212 (blue) and in the heavy-fermion metal $CeCoIn_5$ (red), plotted as Δ_0/k_BT_c versus φ, where T_c is 93 K and 2.3 K, respectively.

The two groups used complementary approaches to access the gap anisotropy. Zhou *et al.* imaged the real-space response of electrons to a single impurity[4]. The bound states that form leak out in the directions where the gap is at its minimum, and so are a fingerprint of the intrinsic pairing anisotropy. Allan *et al.*[3] used the method of 'quasiparticle interference'. This exploits the wavelike nature of electrons, whereby standing waves in real space (called Friedel oscillations) are formed when electrons scatter off local impurities. In the normal state (above T_c or above H_{c2}), a Fourier transform of the resulting interference pattern yields the various electron wavelengths, that is, the Fermi surface in reciprocal space. In the superconducting state, the pattern is modified by the direction-dependent gap, which can therefore be inferred. Both groups find that the gap is at its minimum for directions of electron motion along the diagonals of the Brillouin zone (Fig. 1). This is consistent with the d_{x2-y2} symmetry previously inferred from the variations in the thermal conductivity and specific heat of $CeCoIn_5$, which are produced by a magnetic field rotated in the basal plane of the tetragonal crystal lattice[5].

$CeCoIn_5$ therefore seems to have the same pairing symmetry as the cuprates (Fig. 1). However, there is an important difference: although cuprates have only one electron band, or Fermi surface, $CeCoIn_5$ has several. This multiplicity confers extra flexibility for the electrons to maximize pairing, and hence T_c, as they can exploit inter-band interactions, for example. In the iron-based superconductors[6] discovered in 2008, the inter-band interaction between a hole-like Fermi surface at the Brillouin zone centre and an electron-like surface at the zone boundary (Fig. 1) is believed to play a key role in producing the second highest T_c values, after cuprates[7].

In those very first studies of superconducting $CeCoIn_5$, a gap was resolved on only one of the multiple Fermi surfaces of $\mathrm{CeCoIn_5}$, revealing a large gap on a heavy band, with a maximum value $\Delta_0 \sim 2.8\, k_B T_c$. But thermal conductivity studies have shown that the gap in $\mathrm{CeCoIn_5}$ must be very small on some part of the Fermi surface[8]. STS is ideally suited to locate this small gap in k-space, and indeed map out how the gap magnitude varies from band to band.

Several other exciting avenues can be pursued. First, by exploiting the magnetic field dependence of coherence factors, the sign of the pairing function can in principle be accessed. Second, in the normal state of $\mathrm{CeCoIn_5}$, the electron effective mass — a measure of the electron–electron interaction — is tuned by a magnetic field in a way that is suggestive of an antiferromagnetic quantum critical point[9,10]. Band-dependent measurements of the mass by means of quasiparticle interference as a function of field could investigate the possible links between mass enhancement and pairing strength. Third, a detailed study of the intriguing gap seen in the normal state[4] could provide insight into the enigmatic 'pseudogap' of the cuprates. A new era in the study of unconventional superconductors has just begun. ❐

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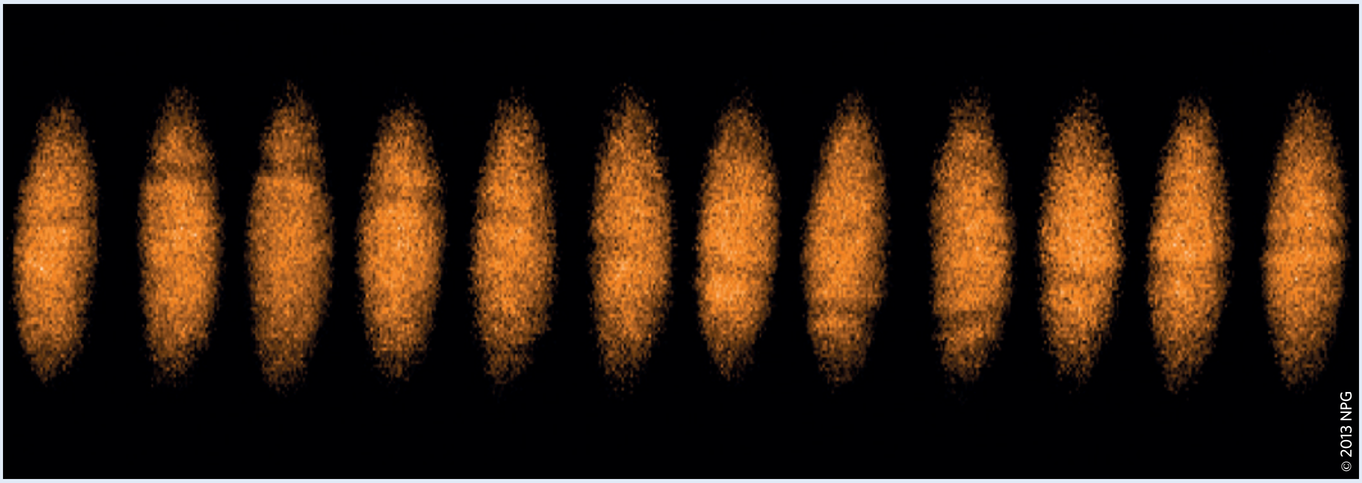
ULTRACOLD GASES

Waves and wiggles



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In 1834, young engineer John Scott Russell observed an unusual phenomenon in the Union Canal — a well-defined solitary wave travelling unchanged at constant velocity, which he called a 'wave of translation'. Fascinated by the effect, Scott Russell set about reproducing it in a water tank to study its properties, but his enthusiasm wasn't shared by his contemporaries and his work was soon forgotten. However, in the 1960s the waves of translation were resurrected in the context of nonlinear phenomena, and are now known as solitons. They appear in unexpected places, from optical fibres to superfluids and superconductors.

As Scott Russell did before them, Tarik Yefsah and colleagues are studying solitons, but rather than a water tank they have developed a much more sophisticated, modern experiment using a superfluid of fermionic atoms (*Nature* **499,** 426–430; 2013). Ultracold lithium atoms are confined in an elongated trap and, as a result of interaction with a laser beam, about half of them experience a phase shift. This creates a soliton — which in the case of a fermionic superfluid is a phase twist in the wavefunction — that can be observed directly as a density-depleted dark region. The soliton propagates back and forth through the superfluid (pictured) like an oscillating spring–mass system.

Yefsah *et al.* tracked the soliton oscillations for different particle-interaction strengths: from a Bose–Einstein condensate (BEC) of tightly bound molecules to a Bardeen–Cooper–Schrieffer (BCS) superfluid of long-range Cooper pairs. In the BEC regime, the soliton is empty — a clearly defined dark region. But as the interaction becomes more BCS-like, the soliton is filled (most probably by unpaired fermions) and its signature fades away. The oscillation period of the soliton increases with the interaction strength and the corresponding effective mass becomes two hundred times larger than the soliton bare mass — which is fifty times larger than predicted by mean-field theory.

This discrepancy could be explained in terms of a serious underestimation of the role of quantum fluctuations and number of unpaired fermions. Thus, these observations are a test of the present theory of the non-equilibrium dynamics in strongly interacting Fermi gases.

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