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Superconductivity

Magnetic glue exposed

Piers Coleman

Overcoming electrons' mutual repulsion is the key to superconductivity. In simple metals, the forces that bind these charged particles in pairs are well understood, but what is the glue in other superconductors?

Physicists are fascinated by the 'glue' that holds matter together. According to quantum mechanics, forces are not instantaneous, but are transmitted by the exchange of tiny packets of energy, or 'quanta', between particles. So electromagnetic forces are produced by the exchange of photons, and the strong forces that keep quarks tightly bound inside protons are driven by the exchange of quanta suggestively called gluons.

But inside metals, different sorts of quanta become possible, and electrons that exchange these quanta can experience new kinds of attractive forces that profoundly change their properties. The most celebrated example of this is superconductivity — which occurs when electrons at low temperature pair up and flow without resistance. Now, on page 340 of this issue, Sato *et al.*[1] reveal a magnetic origin for the 'glue' between electrons in an unconventional superconductor.

In the late 1950s, Bardeen, Cooper and Schrieffer (BCS) showed that superconductivity involves the formation of bound pairs of electrons, named Cooper pairs. BCS argued that the electron pairs were 'glued together' by tiny deformations in the crystal lattice, called phonons, that accompany the electrons' motion. But although phonons were implicated in superconductivity many years before the BCS theory, it was not until the 1960s that it became possible to definitively identify them as the glue in conventional superconductivity.

In the early 1960s, the Russian physicist Eliashberg[2] showed how the electron-pairing forces created by phonons could be elegantly incorporated into BCS theory using a set of equations that now bear his name. It turns out that the exchange of phonons between the electrons in a Cooper pair produces tiny harmonics — wiggles and bumps — in the energy distribution of the electrons that can be detected using electron-tunnelling spectroscopy[3]. In the late 1960s, McMillan and Rowell[4] confirmed the long suspected role of phonons in conventional superconductors. They showed that the phonon energy spectrum measured by neutron scattering from superconducting mercury and lead agreed with the spectrum that they had deduced from their precise electron-tunnelling measurements. In so doing, they also confirmed that the Eliashberg refinement of BCS theory was accurate to about 1%.

The 1970s and 1980s led to the discovery of superconductivity in two new, unconventional classes of material, the heavy-fermion[5,6] and high-temperature[7] superconductors. Conventional superconductivity is suppressed by the tiniest concentration of magnetic atoms, but the unconventional superconductors contain a dense array of magnetic atoms, which appear to be actively involved in electron pairing. This led physicists to consider a new kind of 'magnetically mediated' superconductivity in which the quanta that glue electrons into pairs are derived from magnetic fluctuations[8–12].

Like electrons in atoms, the character of the electron waves in Cooper pairs is labelled *s*, *p* or *d*, depending on the angular momentum of the electrons. Phonon-mediated pairing favours the formation of *s*-wave electron pairs, but magnetic fluctuations favour *p*- or *d*-wave pairs (Fig. 1). This is because magnetic fluctuations develop in metals with strongly interacting electrons: *p*- or *d*-wave pairs form in direct response, lowering the mutual repulsion between the electrons by keeping them further apart. In the unconventional superconductors, neutron scattering experiments have revealed large fluctuations in magnetic spin at low temperatures, which could mediate electron pairing, and several other experiments provide good evidence for the existence of *p*- or *d*-wave electron pairs in these materials.

But despite strong circumstantial evidence for magnetically mediated superconductivity, definitive proof that spin fluctuations are the glue for *p*- or *d*-wave pairing has been hard to come by. This is partly because magnetic fluctuations are far more difficult to characterize than phonons, but also because, unlike phonons, magnetic fluctuations interact with each other, making the theoretical description of magnetically mediated pairing a far more complex problem.

Sato *et al.*[1] provide new evidence for this magnetic glue. They studied the heavy-fermion superconductor UPd_2Al_3, so called because the conducting electrons in it acquire very large effective masses, often hundreds of times that of a free electron. UPd_2Al_3 is one of a handful of heavy-fermion superconductors in which both antiferro-

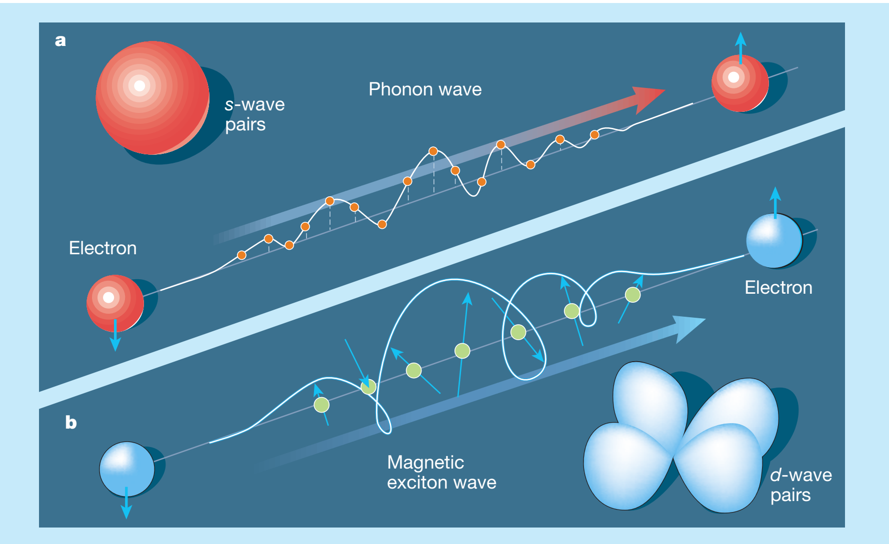

Figure 1 **Two ways to make a metallic superconductor.** a, **In conventional superconductivity the glue responsible for binding electrons into superconducting pairs is derived from the exchange of 'quanta' of lattice vibrations — phonons, shown here as a wave passing through the lattice atoms — that bind electrons into '*s*-wave' pairs.** b, **Sato *et al.*[1] provide new evidence that, in the unconventional superconductor UPd_2Al_3, the glue responsible for the electron pairing derives from the exchange of magnetic quanta — magnetic excitons — that bind the electrons into '*d*-wave' pairs (blue arrows indicate direction of spin).**

magnetism (a type of magnetic order) and superconductivity can coexist. In essence, the work by Sato *et al.* is an attempt to extend the approach of McMillan and Rowell to unconventional superconductivity.

In earlier neutron scattering experiments on UPd_2Al_3, Sato and colleagues[13] detected an excitation in the material's magnetic spin fluctuations, which they identified as a 'magnetic exciton'. Magnetic excitons are a kind of spin wave that ripples through a magnetically ordered medium, but they require a certain amount of energy to become excited. Sato *et al.*[13] noticed that in the normal metallic state, the magnetic exciton is strongly scattered by the heavy electrons in UPd_2Al_3 and has a short lifetime, but that in the superconducting state, it is weakly scattered, with a long lifetime. This suggested that excitation is strongly coupled to the electrons involved in pairing, and it led Sato and colleagues to speculate that the magnetic exciton might indeed be the long-sought glue particle.

To test this idea, Sato *et al.*[1] built a simple model in which the magnetic exciton couples magnetically to the heavy electrons. They found that, with strong coupling, they could account for the dramatic reduction in the excitons' lifetime in the normal metallic state. Their model also explained the appearance of a secondary peak in the exciton spectrum in the superconducting state as the result of an energy gap developing in the heavy-electron spectrum. Finally, in a step that closely parallels the work of McMillan and Rowell, Sato *et al.* used the Eliashberg equations to predict the electron energy spectrum expected from neutron tunnelling measurements. Their model can explain both the observed superconducting transition at a temperature of 2 K, and the fine details of the tunnelling spectra in the superconducting state.

These fascinating results argue strongly that magnetic fluctuations are indeed the glue that drives *d*- or *p*-wave pairing in this unconventional superconductor. But there are still many open questions. UPd_2Al_3 is a rather special case of *d*- or *p*-wave pairing because the electrons move in a magnetically ordered medium. It is this feature that allows the spin fluctuations to move ballistically, enabling them to be regarded like phonons or their free-space cousin, the photon.

The situation in many other unconventional superconductors is not as clear-cut. For instance, in the high-temperature superconductors and many heavy-fermion superconductors, there is no fully developed antiferromagnetic order, and there is no clear separation between the magnetic spin fluctuations and conducting electrons. Here, the glue is much more likely to resemble the 'gluons' that bind quarks inside nucleons, in that the interactions are far stronger and the glue particle only exists as a fleeting entity, rather than as a well-defined excitation. This is the picture that is emerging to explain similar magnetic excitons that have been seen in high-temperature superconductors[14]. Nonetheless, the evidence provided by Sato *et al.* marks an important step forward: introducing us to a material in which magnetically mediated pairing plays a similar role to conventional phonon-mediated pairing. ■

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Structural biology

Protein crystal mimics reality

Robert M. Macnab

Flagellin, a protein in the bacterial flagellar motor, has resisted attempts at three-dimensional crystallization — until now. The crystal structure offers hints as to how filaments are able to switch helical states.

Bacteria such as *Salmonella* and *Escherichia coli* propel themselves through aqueous environments using flagella. The flagellum has two parts: the filament and the motor. The filament is a long, thin, helical structure found outside the cell; when rotated by the motor, embedded in the cell surface, the filament propels the cell along. The filament is made from tens of thousands of copies (subunits) of one protein, flagellin. Changes in the arrangement of these subunits within the filament result in changes in bacterial movement, from 'swimming' to 'tumbling', but how does this molecular switch come about? On page 331 of this issue[1], Samatey and colleagues provide the most detailed picture to date of this interesting biological structure, and make a prediction about the switching event.

Flagellar filaments are organized as follows. Flagellin proteins are arranged, one on top of another, into a protofilament, and 11 of these protofilaments are lined up side by side, forming what looks like a loosely rolled sheet of paper, or hollow cylinder — the flagellar filament (Fig. 1a, overleaf). The protofilaments can be in either of two states, called L (left-handed) and R (right-handed), with all subunits within a given protofilament being in the same left- or right-handed state. The distance between a flagellin subunit and that above or below it (the intersubunit distance) is almost, but not exactly, the same in the L and R states (52.7 Å and 51.9 Å, respectively).

In the abnormal situation in which all 11 protofilaments in a filament are in the same state, the filament is straight. But usually it contains protofilaments in both states, and so is macroscopically helical — an essential feature for propulsion. For example, in the case of the form used for swimming[2], there are nine L and two R protofilaments. The protofilaments have a remarkable capacity to switch between different states in a cooperative fashion. This manifests itself at the macroscopic level as conversion between different helical forms, notably the left-handed form used for swimming (when the motor rotates in an anticlockwise direction) and the right-handed form used for reorientation (tumbling, when the motor rotates clockwise)[3].

High-resolution structural analysis of a three-dimensional crystal of flagellin would help to explain how this molecular switch takes place. But the subunits of filamentous structures often have a mind of their own — they prefer to organize themselves in a long line, the filament's axis. Flagellin is a perfect example. *In vitro*, flagellin can readily form filaments, identical to those formed *in vivo*. But, until now, no one had succeeded in obtaining a three-dimensional crystal of flagellin, and so structural studies[4,5] — even using the most advanced techniques of electron microscopic image analysis and X-ray-fibre diffraction — gave a resolution of only about 10 Å. This is good enough to yield information about the shape and overall organization of the subunits. But it does not give the atomic resolution (2 Å or better) needed fully to understand a protein's secondary structure (how particular regions fold, for example into α-helices) and tertiary structure (overall conformation). Nor can it provide detailed information about quaternary structure — the interfaces between proteins — which is so important in a structure such as the flagellar filament.

Samatey *et al.*[1] describe how they precisely and judiciously cut off the amino- and carboxy-terminal ends of the flagellin, so that