

## SUPERCONDUCTORS

## The electron shatters

The electron is responsible for charge and spin transport in conventional metals. In contrast, the existence of well-defined electronic excitations in the metallic state of high-temperature superconductors is highly debated.

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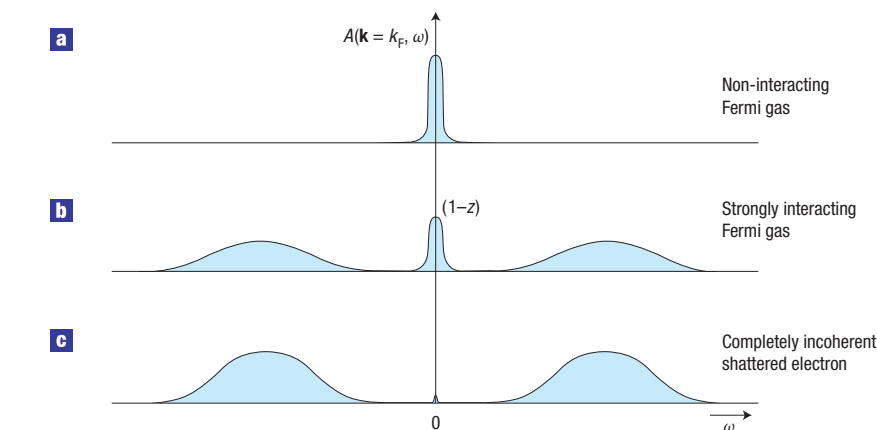
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**A**n electron is an elementary particle with charge  $-e$  and spin  $1/2$ . Inside a metal, a large number of negatively charged electrons interact with each other and with the positively charged nuclei. The metallic ground state is described by a filled Fermi sea of electrons. The low-energy properties of conventional metals can be understood in terms of excitations (above this Fermi sea) that retain the spin and charge quantum numbers of the bare electron. These low-energy excitations of the electron liquid are called Landau quasiparticles. Lev Landau's theory of Fermi liquids has been very successful in describing the thermodynamic and transport properties of conventional metals in terms of weakly interacting quasiparticles with an effective mass  $m^*$  that is larger than the bare electron mass.

However, the normal (non-superconducting) state of the high-temperature superconductors has long been suspected of being 'different'<sup>1,2</sup>. In the proposed novel metallic states above the superconducting transition temperature, the electron is not a well-defined excitation, Fermi-liquid theory does not apply and interactions lead to qualitative changes. On page 210 of this issue, Philip Casey *et al.*<sup>3</sup> provide experimental and theoretical evidence that the electron breaks up in the normal state of the copper-oxide superconductor  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ , leaving no vestige of the original particle.

The authors describe the latest developments in angle-resolved photoemission spectroscopy (ARPES), an experimental technique for studying electronic excitations in solids, and present new ideas in the theoretical description of the electronic spectral function in a state of matter that cannot be described within the Fermi-liquid framework. Both of these could be very important in future studies of novel materials. They make the case that



**Figure 1** The spectral function  $A(\mathbf{k}, \omega)$ . **a**, In a non-interacting Fermi gas, the electrons are well-defined and show up as a sharp  $\delta$ -function at zero frequency. **b**, Once interactions become important, as in a Fermi liquid, some of the spectral weight is transferred to incoherent features, but the quasiparticle (interacting electron) carries a reduced weight  $Z$ . **c**, In the proposed 'normal' state, there is no well-defined particle and all the weight lies in the incoherent features.

the non-Fermi-liquid spectra proposed by Anderson<sup>3,4</sup> provide an excellent fit to the experimental data with a minimum number of fit parameters.

Angle-resolved photoemission permits us to measure the spectral function  $A(\mathbf{k}, \omega)$ , the probability of finding an electron inside the material with momentum  $\mathbf{k}$  and energy  $\omega$  (with respect to the minimum excitation energy, or Fermi energy  $E_F$ )<sup>5,6</sup>. An incident photon knocks out an electron from inside the material. By measuring the energy of the ejected electron and the direction in which it emerges, it is possible to obtain  $f(\omega)$  times  $A(\mathbf{k}, \omega)$ . Here  $f(\omega)$  is the Fermi function, as only occupied states are probed. The measured  $A(\mathbf{k}, \omega)$  gives us information about the interaction of the electron with all other degrees of freedom inside the solid.

Whether the electron is a well-defined excitation is quantified by the shape of the spectral function  $A(\mathbf{k}, \omega)$ . In general, it is composed of two pieces: a sharp coherent piece in which the electron character is left undisturbed, and a broad incoherent feature. The broad feature arises because the act of exciting a single electron necessarily leads

to many electrons being excited as a result of interactions.

Figure 1 shows a schematic picture of the spectral function  $A(\mathbf{k}, \omega)$  at the Fermi surface ( $k = k_F$ ) at absolute zero. For a non-interacting system,  $A(\mathbf{k}, \omega)$  is a  $\delta$ -function (Fig. 1a) with weight  $Z = 1$ . With increasing interactions, the quasiparticle weight  $Z$  in the  $\delta$ -function is reduced and the missing spectral weight  $(1 - Z)$  is transferred into a broad feature (Fig. 1b). However, the fact that  $Z$  is non-zero implies that a Landau quasiparticle exists: a fraction  $Z$  of the electron still remains intact as a sharply defined excitation. In an ARPES experiment this appears as a sharp resolution-limited peak. On the other hand, if the electron completely shatters, as shown in Fig. 1c, then  $Z \rightarrow 0$  and the spectral function becomes totally incoherent.

The new experimental development in this paper<sup>3</sup> is the use of low-energy photons from a laser source. This seems to give results that are different from earlier ARPES data<sup>5,6</sup>. In particular, the measured spectra in laser ARPES exhibit narrower spectral features and diminished extrinsic backgrounds, compared with data obtained from higher-energy

synchrotron or helium-lamp studies. But the low energy of the laser photons raises questions about the validity of the 'sudden approximation': can one ignore final-state interaction effects, which should be stronger the lower the kinetic energy of the outgoing electron? Further studies will undoubtedly clarify this and other issues about the interpretation of laser ARPES. For now, the authors make the reasonable argument that sharper spectra with smaller backgrounds provide better insight into the intrinsic properties of the spectral function, which are crucial for settling the question of whether or not the electron is a well-defined excitation.

Now we come to the second important part of the paper of Casey and colleagues: the theoretical work proposing that the so-called 'strange metal' region of the cuprate phase diagram does not support well-defined electronic excitations. The  $\delta$ -function in  $A(\mathbf{k}, \omega)$  for a Fermi liquid is equivalent to a 'pole singularity' in the Green's function. Phil Anderson argues that in the strange metal the Green's function of the electron shows a qualitatively different 'branch cut singularity' rather than a pole<sup>4</sup>.

There are two ingredients that go into Anderson's result. The first is the idea of Gutzwiller projection: strong local repulsion between electrons leads to a low-energy Hilbert space, in which two electrons cannot sit at the same site. In other words, all configurations of electrons with double-occupancy must be projected out.

Thus the physics of a high-temperature superconductor differs from that of a conventional metal. The effects of projection have led to detailed quantitative insights into the properties of the superconducting state below the transition temperature  $T_c$ , building on the 'resonating valence bond' proposal<sup>7</sup> in thinking about the superconducting state as a 'projected' paired wavefunction. Here<sup>3</sup>, Anderson investigates the Green's function of a projected normal Fermi system.

Anderson invokes ideas going back to the 1960s on the orthogonality catastrophe and X-ray edge singularities in metals. The photoemission process makes a hole in the metal as an electron is emitted from the material, and it is the spectral function of this hole that is measured. Anderson argues that the response of the Gutzwiller projected metal to this hole is formally similar to that of the sudden appearance of a 'potential', leading to an orthogonality catastrophe with quasiparticle weight  $Z = 0$  and a characteristic power law in the spectral function.

The resulting power-law lineshape for  $A(\mathbf{k}, \omega)$  is found to describe the laser ARPES data well with one fitting parameter and a small background subtraction. Although the data are also consistent with the more conventional Fermi-liquid spectral function fits, the authors say that they would require additional fitting parameters and background subtraction. And finally the aim is not to just fit data.

These issues will be debated but the paper of Casey *et al.* is exciting as it opens up the tantalizing possibility of an unusual 'normal' state with  $Z = 0$ . Already ARPES has gone through a revolution in terms of improvements of the energy and momentum resolution, and this paper identifies some of the directions for future investigations. Computational approaches are also challenged to calculate the spectral function without approximations in such strongly interacting systems.

Does the electron really shatter? What is the significance of such a discovery if it is indeed true? Essentially, we would need a new theoretical framework, a new paradigm, to describe a system composed of incoherent lumps of charge and spin. The present Fermi-liquid theory that has been a cornerstone of condensed-matter physics is no longer valid.

#### References

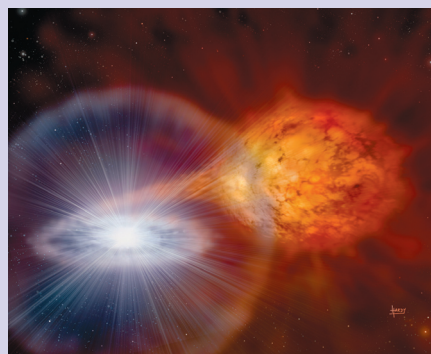
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## ASTROPHYSICS

### Dust before the storm

Dust generally follows an explosion, but astronomers have found what seems to be the opposite case in RS Ophiuchi. Using the twin telescopes of the Keck Interferometer in a 'null' mode, which suppresses the light of a star by a dark fringe such that faint objects nearby can be resolved, Richard Barry and co-workers studied this recurring nova four days after its latest outburst on 12 February 2006 (*Astrophys. J.* doi:10.1086/529422; 2008). Previous recorded events occurred in 1898, 1933, 1958, 1967 and 1985.

The exploding star is a white dwarf, whose surface undergoes nuclear explosions. Its companion red giant sheds gaseous matter that the white dwarf incorporates. Whenever the surface temperature of the growing white dwarf reaches some critical value, a thermonuclear explosion ensues and the luminosity increases 600-fold.



A thermonuclear explosion is also the engine for a supernova blast, but that involves the core of a massive star and not only its surface.

Although this binary system has been studied using many telescopes at different wavelengths, only the interferometry method provides spatial resolution of

the emission components. And in the bright zone surrounding the explosion, there was no dust — but further out, well beyond the blast wave, silicate dust abounds.

To explain all the observations to date, including how the dust got there, requires a new model. In the current model, the interaction between the matter ejected by the white dwarf during the blast and the wind from the red giant creates a shock wave. The observations of Barry *et al.* suggest that the motion of the binary system through the cool wind causes the shock wave to have a spiral pattern, which leads to density enhancements that enable dust to form from the cooler atoms, in a 'pinwheel' pattern. Of course, this pinwheel structure was destroyed during the latest blast, but it should build up again if the model is correct.

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