HIGH-TEMPERATURE SUPERCONDUCTIVITY

Electrons scatter as they pair

The pairing of electrons in high-temperature superconductors is anisotropic. Measurements now reveal their scattering to bear the same anisotropy, providing insights into the nature of the normal state and the origin of superconductivity.

LOUIS TAILLEFER

is in the Département de physique, Université de Sherbrooke, 2500 boul. Université, Sherbrooke J1K 2R1, Canada, and the Canadian Institute for Advanced Research.

e-mail: louis.taillefer@usherbrooke.ca

Twenty years after the discovery of high-temperature superconductivity in copper oxides, the fundamental connection between the robust superconducting state — which can survive from absolute zero to almost halfway to room temperature — and the strange metallic state out of which it emerges is still a matter of intense debate[1]. A key signature of this strangeness is the strikingly linear temperature dependence of the electrical resistance above T_c, the superconducting transition temperature. On page 821 of this issue[2], Majed Abdel-Jawad and co-workers investigate this connection and reveal that the linear resistivity originates from an anisotropic scattering process that vanishes and peaks precisely where the anisotropic superconducting gap is known to vanish and peak. This 'matching of anisotropies', combined with the known 'matching of onsets' as a function of carrier concentration p, strongly suggests that a single underlying interaction governs both pairing and scattering.

Resistance to the flow of electric current in a material arises because mobile electrons are scattered, whether by vibrations in the crystal lattice (phonons), fluctuating magnetic moments (spin fluctuations) or other electrons. The growth of this resistance is roughly proportional to temperature in copper oxides, and is due to a temperature-dependent inelastic scattering rate, in this case $\Gamma \sim T$. To figure out what scattering process is responsible for the anomalous linear-T dependence, it can be very useful to know its anisotropy — how Γ depends on the direction of electron motion, within the CuO_2 planes of the layered structure. To access this information, a simple measurement of the in-plane resistance as a function of angle won't do — by symmetry a square lattice yields an isotropic resistivity, given by an angular average over the underlying, possibly anisotropic, Γ.

To circumvent this problem, Abdel-Jawad *et al.* use a clever, but counter-intuitive approach: they send the current along the tetragonal axis, perpendicular to the

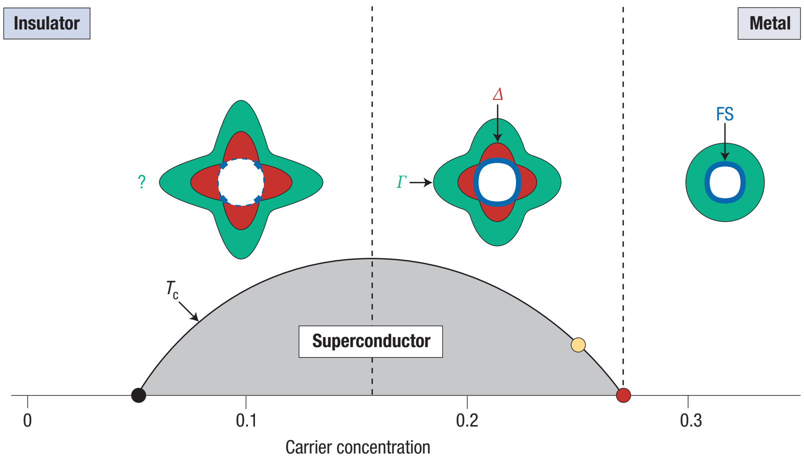

Figure 1 Generic phase diagram of high-temperature superconductors. As the carrier concentration p increases, the electronic state goes from insulator to metal, with superconductivity intervening between two critical points (black and red circles) and below a critical temperature T_c. Three regions can be delineated according to the Fermi surface (FS; in blue), superconducting gap (Δ; in red) and scattering rate (Γ; in green): right, the strongly overdoped region ($p > 0.27$), characterized by a full cylindrical Fermi surface, no superconductivity and an isotropic scattering rate; centre, the overdoped region ($0.16 < p < 0.27$), marked by the simultaneous appearance — at the quantum critical point (red circle) — of anisotropic (d-wave) superconductivity and anisotropic scattering; left, the underdoped region ($p < 0.16$), marked by the destruction of the Fermi surface in directions of maximum scattering (and maximum gap), leaving only 'arcs' or points as remnants. In the overdoped region, the anomalous scattering resolved by Abdel-Jawad *et al.* at $p = 0.25$ (yellow circle) — anisotropic and linearly proportional to temperature ($\Gamma \sim T\cos^2(2\varphi)$) — seems to correlate well with the pairing gap Δ in both φ and p dependence. In the underdoped region, the anomalous scattering might be responsible for the anisotropic obliteration of the Fermi surface.

CuO_2 planes, but apply a strong magnetic field **H** with an in-plane component. The field serves two purposes: it suppresses superconductivity, and it forces electrons to move in orbits that sample in-plane directions. At fixed magnetic field (say 45 T), ρ is found to depend intricately on both the (polar) angle θ between **H** and the plane and the (azimuthal) angle φ between **H** and the Cu–O–Cu bond direction in the CuO_2 plane. At low temperature (say 4.2 K), the intricate pattern, called AMRO (angle-dependent magneto-resistance oscillations), is entirely determined by the topology of the Fermi surface. The scattering rate is accessed by increasing the temperature, which gradually suppresses the structure in the pattern. The key is the non-uniform suppression, implying that different orbits (corresponding to different θ angles) experience different scattering strengths. Through detailed analysis, the authors are able to extract the φ dependence of Γ.

They find $\Gamma = \Gamma_0 + aT^2 + bT\cos^2(2\varphi)$. The isotropic part is standard for metals: the sum of impurity scattering (Γ_0) and electron–electron scattering (aT^2). The last term is the anomalous one, and the focus of our interest. The linear T dependence of the in-plane resistivity comes from this term, as shown by the authors who use their extracted $\Gamma(\varphi)$ to calculate $\rho(T)$; they find excellent quantitative agreement with the measured resistivity[2]. Note that in $Tl_2Ba_2(Ca_0)Cu_1O_{6+\delta}$ (Tl-2201) samples such as theirs, where $p = 0.25$, the resistivity is not perfectly linear, but best described by $\rho = \rho_0 + AT^2 + BT$ (refs 3,4). Their key finding is that the anomalous scattering is profoundly anisotropic. It goes to zero at $\varphi = \pi/4$ and is maximum at $\varphi = 0$. This angle dependence mimics the d-wave superconducting gap, $\Delta = \Delta_0\cos(2\varphi)$. As anisotropic pairing comes from anisotropic interactions, it is natural to ask whether the anomalous scattering and the superconductivity share a common origin. What might be the nature of this underlying interaction? Antiferromagnetic fluctuations certainly come to mind as one possibility, given their known tendency to favour d-wave pairing[5].

In pursuing this connection, the authors highlight two experimental facts. First, the appearance of a linear-T term in the resistivity — absent at $p = 0.3$ (ref. 6) but present at $p = 0.25$ (refs 3,4) — coincides roughly with the onset of superconductivity at $p = 0.27$, as sketched in Fig. 1. This 'matching of onsets' reinforces the link suggested by the 'matching of anisotropies'. Secondly, the linear T dependence persists to millikelvin temperatures[3,4]. If it is caused by the thermal excitation of magnetic fluctuations, these must have a vanishing characteristic energy — the standard signature of a quantum critical point (QCP), the zero-temperature phase transition between distinct ground states[7]. The only unambiguous QCP in that region of the phase diagram is the superconducting QCP itself (red circle in Fig. 1), not a magnetic QCP. Note, however, that it would not be the first time that a magnetic QCP is avoided in favour of superconductivity[8,9].

In future work, it will be of great interest to track the anomalous scattering as a function of p, in particular as p is reduced. The linear term in the resistivity becomes much stronger near optimal doping ($p = 0.16$) — roughly by a factor 10 — as does the superconducting gap Δ_0 — by a factor 6 or so (a 'matching of magnitudes'?). Will the characteristic angle dependence of Γ follow suit? Below optimal doping ($p < 0.16$), the system enters the mysterious 'pseudogap phase', the subject of much speculation and debate[1]. There, the Fermi surface itself seems to be destroyed[10] — in anisotropic fashion, with maximal effect where scattering is strongest (see Fig. 1). Might this correlation lead us to the elusive underlying interactions of the pseudogap phase?

We can bet on one thing: the magneto-transport will be profoundly altered, and whether electrons can even travel around closed orbits remains to be seen. In such a context, AMRO — regarded as a property of a coherent Fermi surface — may not survive. Conversely, if AMRO is indeed observed, much of the ongoing speculation will be laid to rest.

REFERENCES

1. Bonn, D. A. *Nature Phys.* **2,** 159–168 (2006).
2. Abdel-Jawad, M. *et al. Nature Phys.* **2,** 821–825 (2006).
3. Mackenzie, A. P., Julian, S. R., Sinclair, D. C. & Lin, C. T. *Phys. Rev. B* **53,** 5848–5855 (1996).
4. Proust, C. *et al. Phys. Rev. Lett.* **89,** 147003 (2002).
5. Norman, M. R. in *Handbook of Magnetism and Advanced Magnetic Materials* Vol. 5, Ch. 4 (Wiley, in the press); preprint available at http://arxiv.org/cond-mat/0609559 (2006).
6. Nakamae, S. *et al. Phys. Rev. B* **68,** 100502 (2003).
7. Coleman, P. & Schofield, A. J. *Nature* **433,** 226–229 (2005).
8. Paglione, J. *et al. Phys. Rev. Lett.* **91,** 246405 (2003).
9. Bianchi, A. *et al. Phys. Rev. Lett.* **91,** 257001 (2003).
10. McElroy, K. *Nature Phys.* **2,** 441–442 (2006).

ERRATUM

Coherence in molecular nitrogen

MARKUS ARNDT

Nature Physics **1,** 19–20 (2005).

In this News & Views piece, reference 3 contained the wrong page numbers. The correct reference is:

3. Rolles, D. *et al. Nature* **437,** 711–715 (2005).