Superconductivity

Shine a light

Michael Norman

Copper oxides superconduct at unusually high temperatures. New evidence from optical studies highlights the nature of the many-body interactions involved.

Throughout the history of superconductivity, optical spectroscopy — through the scattering of light by a material — has been a vital tool. It was the existence of a gap in the excitation-energy spectrum of electrons, first observed in optical studies, that set Bardeen on the path to the celebrated Bardeen–Cooper–Schrieffer theory of superconductivity. That theory, in which electrons move as Cooper pairs, is now the established description of the low-temperature phenomenon. On page 714 of this issue, Hwang *et al.*[1] have again demonstrated the power of optics to reveal fundamental information about superconductivity. This time, however, the revelations pertain to the underlying interactions in high-temperature superconductivity.

For copper oxides, the transition temperature at which they become superconducting is much higher than in other materials — hence the name high-temperature superconductors. Hwang *et al.* looked at the so-called optical self-energy of a bismuth-containing copper oxide (known as Bi-2212). This self-energy quantifies the deviation of the measured energy spectrum of electrons in the material from that predicted by the simple Drude theory of elementary metals. In the Drude theory, electrons are treated as hard spheres that travel in straight lines between collisions; deviations from this behaviour are thus a measure of the strength of the many-body interactions that the electrons undergo.

Hwang *et al.*[1] find that, for temperatures above the superconducting transition temperature, this self-energy has a rather broad and featureless distribution, up to very high electron excitation energies. Such behaviour is inconsistent with that expected if the moving electrons are interacting with phonons — vibrations in the atomic lattice — as occurs in low-temperature superconductors. Instead, Hwang *et al.* conclude that the self-energy distribution is due to interactions between the electrons themselves. This finding supports a large body of theoretical work that argues that copper oxide superconductors are indeed fundamentally different from their low-temperature counterparts. As Hwang *et al.* also suggest, this optical self-energy can be considered as a measure of the 'glue' that binds electrons into Cooper pairs, binding that in turn gives rise to superconductivity.

Even more interesting are their results for Bi-2212 at lower temperatures. As the material is cooled, a sharp peak develops in the optical self-energy. This behaviour is analogous to that seen for copper oxides in other experiments based on photoemission. In those experiments, the 'dispersion relation' between the energy and momentum of the electrons is measured at different temperatures. Figure 1 shows the typical variation[2] of energy with momentum for a copper oxide sample (optimally doped) at two different temperatures: at 140 K, which is above the transition temperature for the sample, and at 40 K, which is below the transition temperature. The deviation of the measured dispersion from its bare predicted value is proportional to the electron self-energy. Above the transition temperature, the dispersion is rather featureless, although it is shifted relative to its bare value; below the transition temperature, a characteristic S-shaped curve develops. The maximum amplitude of this 'S' represents the peak in the electron self-energy.

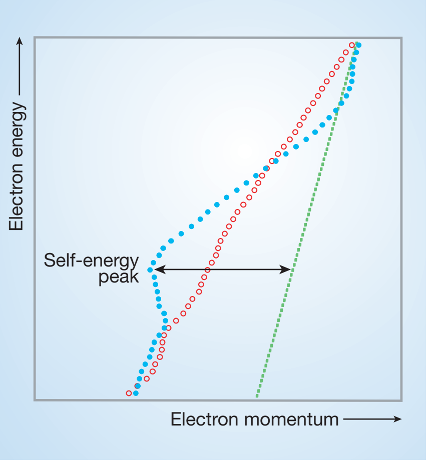

Figure 1 **Self-energy and the superconductor. Measured in photoemission experiments[2] on optimally doped Bi-2212, the dispersion relation between the energy and momentum of electrons in the material is shown at different temperatures. The transition temperature at which the material becomes superconducting is 90 K; data are shown for temperatures each side of that mark, at 40 K (blue dots) and 140 K (red circles). The green dashed line is the bare theoretical estimate. At 40 K, an S-shaped curve appears in the dispersion; the maximum displacement of the data curve from the theory corresponds to a peak in the electron self-energy. This effect is analogous to that now observed by Hwang *et al.*[1] in optical studies. These authors argue[1] that the peak is caused by the interaction of electrons with a magnetic resonance.**

Such S-shaped dispersions are well known in many-body physics. They are a consequence of the interaction of the electrons with a collective mode that is sharp in energy. Although Lanzara *et al.*[3] have advocated that this mode is a phonon, it has been suggested by other groups[2,4] (including mine) that the mode is a magnetic resonance, evidence of which has been seen in inelastic neutron-scattering experiments[5].

The data put forward by Hwang *et al.*[1] strongly support the magnetic-resonance interpretation of the self-energy peak. They have tracked the optical self-energy peak at various temperatures over a wide range of chemical doping (that is, varying the amount of mobile charge-carriers added to the sample, which affects its performance as a superconductor) and they find that the peak is directly correlated with the magnetic resonance. They also find that, as the doping increases, the peak eventually disappears at a doping level for which the superconductivity is still strong — electrons are still joined into Cooper pairs, so the peak itself, they suggest, cannot represent their binding glue.

Although this assertion is true, it should be noted that the magnetic resonance is a feedback effect associated with the onset of superconductivity — thus it does not cause superconductivity but is caused by it[6]. The reason for its disappearance at high doping levels is the expectation that, as the many-body interactions weaken with increased doping (which is supported by the optics[1] and photoemission[4] measurements), the resonance will in turn weaken and disappear.

But the fact that the optical self-energy peak grows continuously out of the broad background as the temperature is lowered, and that it has, moreover, a magnitude comparable to that of the background, indicates that the background 'glue' and the peak have a common origin. Because the peak is magnetic in nature, this implies that the glue is magnetic as well. Consequently, Hwang *et al.*[1] have provided strong evidence that the origin of high-temperature superconductivity in copper oxides is indeed connected with magnetic correlations. This work will be a great encouragement to those pursuing a magnetic pairing model for copper oxide superconductivity. ■

Michael Norman is at the Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA.
e-mail: norman@anl.gov

1. Hwang, J., Timusk, T. & Gu, G. D. *Nature* **427**, 714–717 (2004).
2. Kaminski, A. *et al. Phys. Rev. Lett.* **86,** 1070–1073 (2001).
3. Lanzara, A. *et al. Nature* **412,** 510–514 (2001).
4. Johnson, P. D. *et al. Phys. Rev. Lett.* **87,** 177007 (2001).
5. Rossat-Mignod, J. *et al. Physica C* **185–189,** 86–92 (1991).
6. Abanov, Ar. & Chubukov, A. V. *Phys. Rev. Lett.* **83,** 1652–1655 (1999).