Copper oxide superconductors

Sharp-mode coupling in high-T_c superconductors

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In conventional superconductivity, sharp phonon modes (oscillations in the crystal lattice) are exchanged between electrons within a Cooper pair, enabling superconductivity. A critical question in the study of copper oxides with high critical transition temperature (T_c) is whether such sharp modes (which may be more general, including, for example, magnetic oscillations) also play a critical role in the pairing and hence the superconductivity. Hwang *et al.* report evidence that sharp modes (either phononic or magnetic in origin) are not important for superconductivity in these materials[1], but we show here that their conclusions are undermined by the insensitivity of their experiment to a crucial physical effect[2–7].

The optics experiment performed by Hwang *et al.* measures a momentum average and is therefore not a sensitive probe when the signal is strongly momentum dependent, as it is for these materials. Existing angle-resolved photoemission (ARPES) data show that in the strongly overdoped regime (with $T_c = 58$ K) there is a prominent 'kink' that is indicative of a peak in the self-energy[2] (Fig. 1). Figure 1b reveals a clear dispersion kink in the superconducting state near 40 meV (arrow). The strong presence of the mode signal in this comparably overdoped sample is in contradiction of the central claim of Hwang *et al.*[1].

Figure 1c, d shows that the kink strength (or the peak height of the extracted self-energy, $Re\Sigma$) from an overdoped sample with T_c of about 71 K is hardly detectable near the node, but is quite strong near the antinode. Hwang *et al.* make no mention of the clear, positive ARPES signal at the antinode, which would otherwise have ruled out their conclusion[1].

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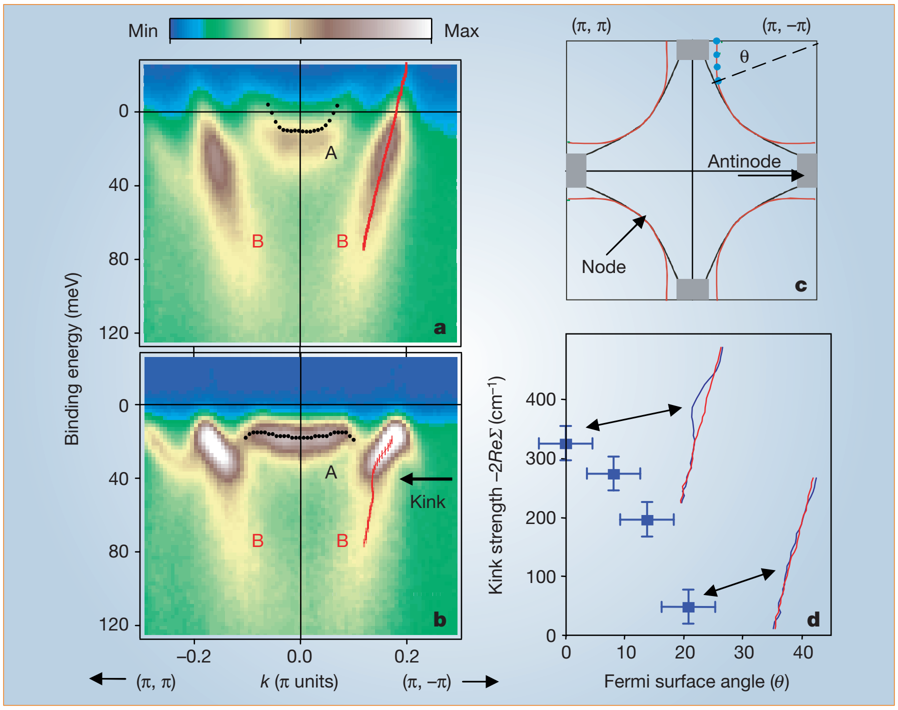

Figure 1 Angle-resolved photoemission (ARPES) data showing a kink in a heavily overdoped $T_c = 58$ K Bi2212 sample (see ref. 2 for details of variables, symbols and coloration). **a,** Normal-state data ($T = 85$ K) from an overdoped sample near the antinodal region (**c**). **b,** Superconducting-state data from the same sample at 10 K, showing the emergence of a dispersion kink in the bilayer split-B band (arrow). **c, d,** Momentum dependence of the strength of the temperature-dependent kink (the real part of the self-energy Σ, taking the normal-state curve as reference) from an overdoped $T_c = 71$ K sample (**d**), with locations indicated on the Brillouin zone (**c**). The normal (red) and superconducting (blue) dispersion curves for the extreme locations are shown as well. The ARPES spectra discussed in ref. 1 were taken at 45° (the node, for example). Reprinted with permission from ref. 2; copyright (2003) of the American Physical Society.

Hwang et al. *reply* — Our optical technique has the advantage of being a bulk probe, which is less subject to uncertainties in the doping level and in the quality of the surface than ARPES. It is also capable of higher energy resolution and the overall noise level is lower. The disadvantage is that it gives momentum-averaged properties.

In light of these differences, it came as a surprise to us that our reported optical self-energies[1] were able to track in accurate detail the ARPES self-energies of Johnson *et al.*[2]. Our data indicate that, as a function of doping, not only could both optical and ARPES techniques resolve the sharp mode from the background but also that the sharp-mode intensity decreases uniformly, disappearing completely at a doping level of 0.23. As superconductivity is still strong at this doping level, with a T_c of 55 K, we conclude that the sharp mode is not an important contributor to high-temperature superconductivity.

Cuk *et al.*[3] make the points that optical data may be insensitive to strongly momentum-dependent signals because they are momentum-averaged, and also that in their ARPES data[4] for momenta near the antinodal point (π, 0), the sharp resonance persists in the highly overdoped region and does not disappear as we claim.

Although the measurements of Johnson *et al.*[2] were performed at the nodal point, the weakening of the resonance also takes place at the antinodal point, as indicated by other ARPES work[5]. As shown in Fig. 2, self-energy effects at (π, 0) are strongly doping dependent, joining the normal-state background at a doping level of 0.24 — just as they do in our optical results and in the ARPES data of Johnson *et al.*[2] at the nodal point. All three experiments show the same strong doping dependence.

It is therefore surprising that the work of Gromko *et al.*[4] fails to confirm these results. These authors do not present doping-dependent plots of the self-energy, but a visual inspection of Fig. 2 of ref. 4 suggests that the self-energy effects are almost doping

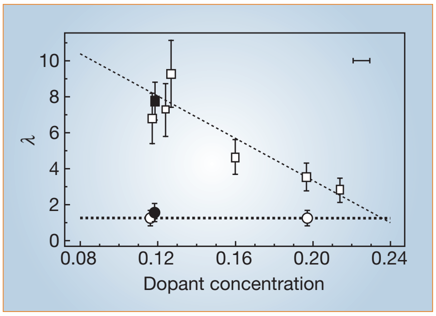

Figure 2 The coupling-strength parameter λ as a function of dopant concentration (see Fig. 3 in ref. 5). Squares, superconducting state; circles, normal state; open symbols, bonding band; filled symbols, antibonding band. Dashed lines are straight-line fits to the data. Horizontal bar, experimental error in the dopant concentration. Reprinted with permission from ref. 5; copyright (2003) of the American Physical Society.