Copper oxide superconductors

Sharp-mode coupling in high-T_c superconductors

Arising from: J. Hwang, T. Timusk & G. D. Gu *Nature* **427,** 714–717 (2004)

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].

T. Cuk*, Z.-X. Shen*, A. D. Gromko†, Z. Sun†, D. S. Dessau†

**Department of Applied Physics, Physics and Stanford Synchrotron Radiation Laboratory, Stanford University, Stanford, California 9430, USA*
e-mail: tanjacuk@stanford.edu
†*Department of Physics, University of Colorado, Boulder, Colorado 80309, USA*

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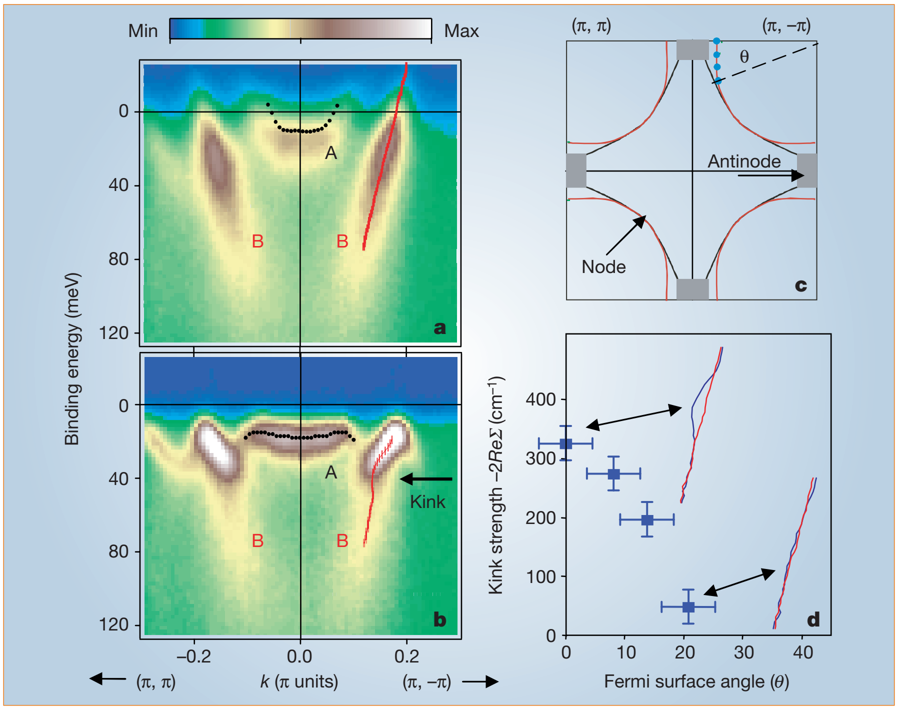

Figure 1 Angle-resolved photoemission (ARPES) data showing a kink in a heavily overdoped $T_c = 58$ K Bi2212 sample (see ref. 2 for details of variables, symbols and coloration). **a,** Normal-state data ($T = 85$ K) from an overdoped sample near the antinodal region (**c**). **b,** Superconducting-state 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

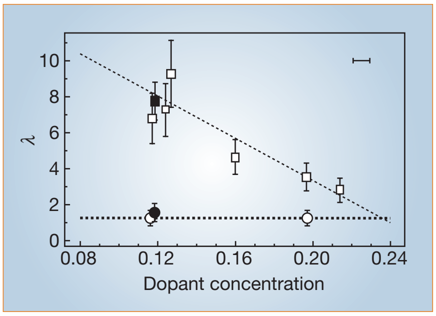

Figure 2 The coupling-strength parameter λ as a function of dopant concentration (see Fig. 3 in ref. 5). Squares, superconducting state; circles, normal state; open symbols, bonding band; filled symbols, antibonding band. Dashed lines are straight-line fits to the data. Horizontal bar, experimental error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

independent — in contrast to the marked doping dependence reported by Kim *et al.*[5]. One reason for the disagreement may be the difficulty in controlling the doping level in the surface layers under the ultra-high-vacuum conditions used in the ARPES experiments.

Jungseek Hwang*, Thomas Timusk*, Genda D. Gu†
**Department of Physics and Astronomy, McMaster University, Hamilton, Ontario L9H 5M3, Canada*
e-mail: timusk@mcmaster.ca
†*Department of Physics, Brookhaven National Laboratory, Upton, New York 11973-5000, USA*

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Asteroseismology

Oscillations on the star Procyon

Arising from: J. M. Matthews *et al. Nature* **430,** 51–53 (2004)

Stars are spheres of hot gas whose interiors transmit acoustic waves very efficiently. Geologists learn about the interior structure of Earth by monitoring how seismic waves propagate through it and, in a similar way, the interior of a star can be probed using the periodic motions on the surface that arise from such waves. Matthews *et al.* claim that the star Procyon does not have acoustic surface oscillations of the strength predicted[1]. However, we show here, using ground-based spectroscopy, that Procyon is oscillating, albeit with an amplitude that is only slightly greater than the noise level observed by Matthews *et al.* using spaced-based photometry.

The new spectrograph HARPS[2] (for High-accuracy Radial-velocity Planet Searcher), which was installed last year on the 3.6-metre telescope of the European Southern Observatory (La Silla, Chile), was optimized for accuracy in Doppler measurement in order to detect extrasolar planets by means of radial-velocity measurements. During its commissioning, we tested its short-time precision on a sample of bright solar-type stars, including Procyon.

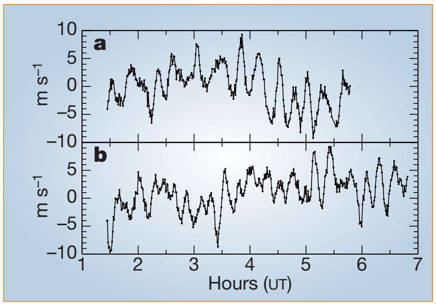

Figure 1 Short sequences of radial-velocity measurements made on Procyon with HARPS spectrograph. **a, b,** Data were collected on **a,** 5 January 2004 and **b,** 6 January 2004. These sequences indicate oscillation modes with periods of around 18 min. UT, universal time.

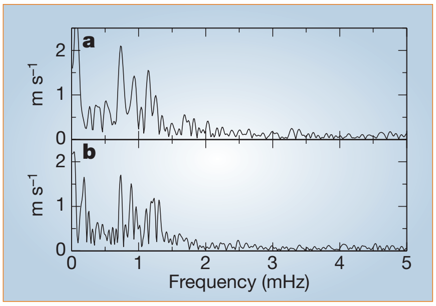

Figure 2 Fourier amplitude spectra of the two short sequences made on Procyon. **a, b,** Signatures of *p*-modes in the frequency range of 0.5–1.5 mHz are evident.

Our measurements on Procyon indicate that there are periodic oscillations of its surface that have a typical period of 18 min (Fig. 1). The apparent amplitude of 4–6 m s^{-1} does not correspond to individual *p*-mode amplitudes, considering that several tens of *p*-modes with similar periods are presumably interfering. Figure 2 presents the Fourier amplitude spectra of the two short time-series obtained on Procyon. No filtering has been applied to the data. Several peaks appear between 0.5 and 1.5 mHz and present the clear signature of acoustic oscillation modes. The correspondence of the main peaks around 1 mHz strongly support the reality of this signature.

Our frequency resolution, which is about 0.55 mHz, does not allow us to resolve individual *p*-modes. The amplitudes of the peaks between 1.0 and 1.5 m s^{-1} probably correspond to two or three times the amplitude of individual modes. The mean white-noise level above 2 mHz is respectively 0.11 m s^{-1} and 0.09 m s^{-1} for the first and second sequences. This result, based on only a few hours of observations, confirms and enforces the previous Doppler ground-based detections[3–6].

Why did the Canadian MOST (for Microvariability and Oscillations of Stars) space mission[1] not detect any signatures of *p*-modes on Procyon? The typical amplitude of *p*-modes is about 0.5 m s^{-1} in radial velocity and the relation for converting between velocity and luminosity amplitudes (given by equation (5) of ref. 7) predicts a luminosity amplitude of only 8–10 p.p.m. This is only slightly greater than the noise level of the satellite obtained after 768 hours of observation. These results indicate that the MOST data are dominated by non-stellar noise, as suspected[8].

However, this conclusion should not overshadow the scientific importance of the Canadian satellite. MOST will lead to breakthroughs on stars with higher oscillation amplitudes, as well as on fast-rotating stars that are not suitable for spectroscopic measurement. The result obtained with HARPS demonstrates the potential of ground-based Doppler measurements for asteroseismology. But for uninterrupted listening to stellar music, a spectrograph like HARPS located in Dome C in Antarctica or in space is needed.

François Bouchy*, André Maeder†, Michel Mayor†, Denis Mégevand†, Francesco Pepe†, Danuta Sosnowska†
**Laboratoire d'Astrophysique de Marseille, Traverse du Siphon, BP8, 13372 Marseille Cedex 12, France*
e-mail : francois.bouchy@oamp.fr
†*Observatoire de Genève, 1290 Sauverny, Switzerland*

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