

**Figure 3. Schizophrenic behavior.** Measurements on underdoped Bi-2212 samples reveal, at low excitation energy, quasiparticle interference patterns, suggestive of superconducting electrons (a) and, at higher energy, striplike stationary patterns (b). (Courtesy of Séamus Davis, Cornell University.)

The results from Hudson's group echo the findings from some angle-resolved photoemission spectroscopy (ARPES) experiments<sup>8,9</sup> and from Raman scattering measurements,<sup>10</sup> all of which have reported evidence for a second gap below  $T_c$  that's smaller than the pseudogap. At the same time, other ARPES groups claim to see just one gap.<sup>11,12</sup>

### Looking in momentum space

A third STM group, led by Davis, has been studying the behavior of underdoped cuprates well below  $T_c$  in both real<sup>4</sup> and momentum space.<sup>13</sup> At recent

conferences, Davis has reported finding different behavior depending on the energy of the tunneling electrons. For low excitation energies (corresponding to low voltage bias), Davis and his collaborators find evidence for a superconducting condensate. For excitation energies of 35 mV and higher, they find only static spatial patterns, indicating that the electrons are partially localized.

Davis's collaborators hail from Cornell, Brookhaven National Laboratory, the University of Colorado in Boulder, the University of Sherbrooke in Canada, and, in Japan, the University of Tokyo,

RIKEN's Discovery Research Institute in Wako, Kyoto University, and the National Institute of Advanced Industrial Science and Technology in Tsukuba.

Traditionally, STM has complemented ARPES, with STM peering into real space and ARPES probing  $k$  space. A number of years ago, theorists noted that one can infer  $k$ -space information from STM. Scanning tunneling microscopes can measure the spatial interference patterns, such as that seen in figure 3a, made by long-lived quasiparticles—electrons from broken Cooper pairs—as they scatter off impurities or other defects. Fourier transforming such patterns yields the  $k$ -space scattering vectors.

Last year, Davis and his colleagues explored a new way to look at STM data in real space, exploiting an asymmetry of the tunneling spectrum of high- $T_c$  superconductors<sup>14</sup> that was noted back in

## physics update

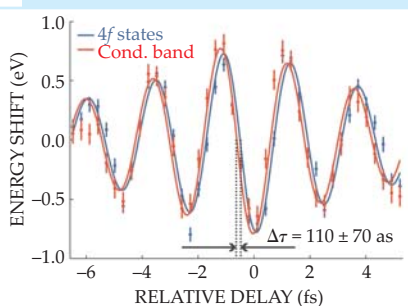
Supplementary material related to these items can be found at [www.physicstoday.org](http://www.physicstoday.org).

**Solid-state attosecond metrology.** Chemistry takes place at the femtosecond speed of atomic motions. In contrast, electrons within atoms, or traveling between neighboring atoms in a molecule or solid, zip along at an attosecond pace (1 as =  $10^{-18}$  s). A European collaboration of physicists, led by Ferenc Krausz at the Max Planck Institute for Quantum Optics in Munich, Germany, has now timed the transport of photoelectrons prior to their emission from tungsten. To do that, the researchers sent through a tube of neon gas an intense femtosecond laser pulse of near-IR light comprising a few well-controlled field oscillations (see PHYSICS TODAY, April 2003, page 27). Through the magic of high-harmonic generation, a single, isolated 300-as coherent extreme UV pulse in a selected spectral band (90–100 eV) was produced. Next, the XUV pulse was directed at a tungsten target where it energized electrons lying close to the sample's surface.

Affected electrons included both the delocalized conduction-band variety and those tightly bound in the tungsten atoms' 4f orbital. Electrons from those two populations were cleverly distinguished: Part of the original NIR laser beam remained coher-

ently linked to the XUV pulse and was engineered to selectively accelerate the conduction-band electrons as they sprang out of the sample's surface ahead of the 4f electrons. The detected time delay of  $110 \pm 70$  as (see the figure) between the two types of photoelectrons was due entirely to propagation differences of the electron wavepackets in the sample. (A. L. Cavalieri et al., *Nature* **449**, 1029, 2007.) —PFS

**Energy-dissipation nanoprobe.** Scanning probe microscopy translates the interaction between a flexible cantilever's super-sharp tip and a sample material into topographical images and force measurements at the nanoscale. However, standard single-frequency SPM cannot reveal certain information, such as the local energy dissipation at a single structural defect—that information is embodied in the quality factor  $Q$  of the vibrating cantilever. Frequency sweeps using standard lock-in techniques can determine  $Q$ , but those techniques are too slow for practical imaging. Now Stephen Jesse and Sergei Kalinin and their collaborators at Oak Ridge National Laboratory, working with Roger Proksch of Asylum Research, have devised a way to excite the cantilever and measure the response over a band of frequencies simultaneously. Known as band excitation (BE), the method is useful for energy-dissipation measurements since the  $Q$  factor can be measured directly, even for low- $Q$  factor environments such as liquids. In just about 1 second, the researchers produced force-distance curves of the tip interactions with cleaved mica; a comparable lock-in scan would take around 30 minutes. The team also showed that  $Q$  decreased sharply when ferroelectric domains nucleated. In addition, the BE SPM imaged in both amplitude (left image) and phase (right image) the flower-like patterns associated with magnetic domains of yttrium-iron garnet, and detected ring-like energy



1995. The asymmetry in STM reflects the strong electron interactions, which make it easier to extract an electron from the superconductor than it is to inject one.<sup>15</sup> Taking the ratio of current at negative bias to that at positive bias can yield a measure of the hole density.

The Cornell collaboration measured that tunneling asymmetry in very underdoped samples<sup>12</sup> of Bi-2212 and of a particular compound of calcium, sodium, copper, oxygen, and chlorine atoms—called Na-CCOC. In both materials, the experimenters found regions where the holes appeared to be localized and ordered in a stripelike pattern. The orientation and location of such regions were random, as shown in figure 3b.

For the work reported at recent conferences, Davis and his coworkers exploited both the space- and momentum-tracking capabilities of STM. They presented evidence for nonlocal states at low-bias voltages and partially localized states at higher bias.

ARPES studies of underdoped cuprates have also uncovered interesting changes in behavior as a function of direction in  $k$  space. Below  $T_c$ , ARPES measurements confirm that the gap has

a cosine variation in momentum space, as expected for electrons that pair in a  $d$ -wave state. Thus, the gap function has four nodal points on the Fermi surface where the gap is zero, and four antinodal points, where the gap is maximal.

Above  $T_c$ , ARPES and other techniques find that the simple  $d$ -wave structure is distorted. Many points along the Fermi surface have no superconducting gap. The locus of those gapless points along a section of the Fermi surface forms an arc centered on the nodal point, while the gap remains open in the antinodal regions. Some theorists have speculated that the nodal region is governed by superconductivity and the antinodal region by a different mechanism; other theorists disagree. (See PHYSICS TODAY, July 2007, page 26.)

In the STM measurements, Davis's group sees the long-lived (nonlocal) quasiparticles near the nodal region of  $k$  space and the partially localized states near the antinodal regions. The experimenters extrapolate an energy scale for the superconductor that increases with decreasing doping, as does the pseudo-gap measured by other experiments.

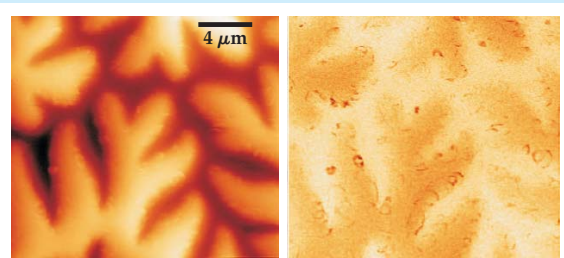
While the new STM experiments—and others—don't settle any questions,

the rich new details they provide are confronting theory in a region where many investigators believe they may find the key to high- $T_c$  superconductivity.

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## References

1. See the reviews of experimental data in S. Hüfner et al., <http://arxiv.org/abs/0706.4282>.
2. K. K. Gomes et al., *Nature* **447**, 569 (2007).
3. M. C. Boyer et al., *Nat. Phys.* (in press).
4. Y. Kohsaka et al., *Science* **315**, 1380 (2007).
5. See the review by Ø. Fischer et al., *Rev. Mod. Phys.* **79**, 353 (2007).
6. C. Howald, P. Fournier, A. Kapitulnik, *Phys. Rev. B* **64**, 100504(R) (2001); S. H. Pan et al., *Nature* **413**, 282 (2001).
7. Y. Wang, L. Li, N. P. Ong, *Phys. Rev. B* **73**, 024510 (2006); L. Li et al., *Nat. Phys.* **3**, 311 (2007).
8. K. Tanaka et al., *Science* **314**, 1910 (2006); W. S. Lee et al., *Nature* **450**, 81 (2007).
9. T. Kondo et al., *Phys. Rev. Lett.* **98**, 267004 (2007).
10. M. Le Tacon et al., *Nat. Phys.* **2**, 537 (2006).
11. T. Valla et al., *Science* **314**, 1914 (2006).
12. A. Kanigel et al., *Phys. Rev. Lett.* **99**, 157001 (2007).
13. K. McElroy et al., *Nature* **422**, 592 (2003).
14. C. Renner, Ø. Fischer, *Phys. Rev. B* **51**, 9208 (1995).
15. P. W. Anderson, N. P. Ong, *J. Phys. Chem. Solids* **67**, 1 (2006); M. Randeria et al., *Phys. Rev. Lett.* **95**, 137001 (2005).



dissipation centers. The researchers anticipate that the BE method will be a fast and sensitive technique for understanding and mitigating energy losses in magnetic, electrical, and electromechanical processes and technologies. (S. Jesse et al., *Nanotechnology* **18**, 435503, 2007.) —JNAM

**A new look at relativistic thermodynamics.** The Lorentz transformations of special relativity (SR) convert time or distance intervals from a resting frame of reference to one that is moving, even at nearly the speed of light. But what temperature will a speeding observer register for a gas in a stationary bottle? A closely related question concerns the correct generalization of Maxwell's velocity distribution to SR, in which more energy means more mass and nothing can move faster than the speed of light. The first answer was put forth by Ferencz Jüttner in 1911, and many variations on his theme have appeared since the 1980s. It is very difficult to maintain a contained gas at relativistic speeds in a terrestrial laboratory, but Jörn Dunkel and his colleagues at the University of Augsburg (Germany) and the University of Seville (Spain) have now performed extensive simulations for a one-dimensional, fully relativistic, two-component gas. The results unequivocally favor the original Jüttner distribution. Furthermore, the simulations illus-

trate that the concepts of thermal equilibrium and temperature can extend to SR only for spatially confined systems. And, measured with a velocity-based statistical thermometer, moving bodies appear neither hotter nor colder than stationary ones. (D. Cubero et al., *Phys. Rev. Lett.* **99**, 170601, 2007.) —PFS

**LHC limit glimpsed at RHIC.** Modern physics has shown that the vacuum is seething with virtual particles springing in and out of existence. In high-energy heavy-ion collisions at accelerators, some of the original beam energy can be consumed by ripping particle-antiparticle pairs out of the vacuum. For example, in the Large Hadron Collider (LHC), soon to turn on at CERN in Geneva, Switzerland, a major source of beam losses for lead-ion collisions is expected to be so-called bound-free pair production (BFPP) in which the countermoving ions don't interact except to spawn an electron-positron pair; the positron goes off to oblivion while the electron latches onto one of the ions, reducing that ion's charge. The modified ion's trajectory will be bent less in the accelerator's magnets and eventually it will smash into the pipe carrying the beams. A shower of particles will result, and the deposited energy will heat up the pipe and the surrounding magnets. Using 6.3-TeV copper ions (about 100 GeV per nucleon), accelerator physicists have now seen the BFPP effect at an existing machine, the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory in New York. They spotted a tiny splash of energy amounting to about 200 mW at the predicted location in the pipe. According to CERN scientist John Jowett, BFPP will produce thousands of times more heat at the LHC than it did at RHIC, possibly quenching a few of the LHC's superconducting magnets and thus limiting the LHC's peak luminosity for heavy-ion physics. (R. Bruce et al., *Phys. Rev. Lett.* **99**, 144801, 2007.) —PFS ■