Learning about High-T_c Superconductors from Their Imperfections

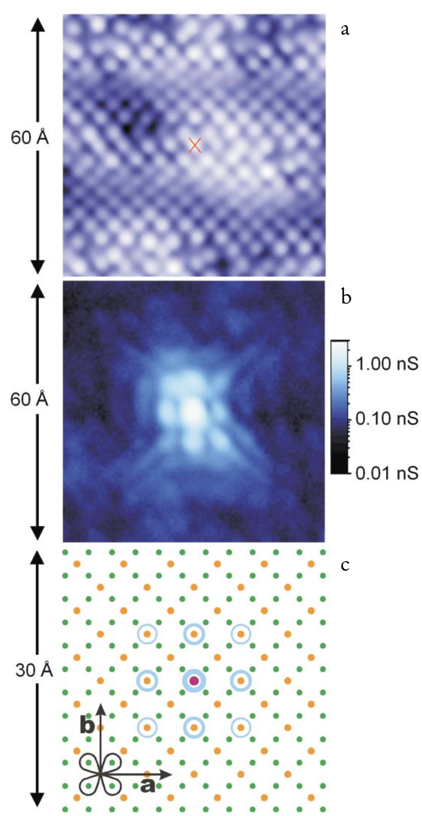
In the old nursery rhyme, little Jack Horner stuck in his thumb and pulled out a plum. That's more or less what experimenters from the University of California, Berkeley, and the University of Tokyo did recently: They stuck a zinc atom into the copper site of a high-T_c superconductor and extracted a plum of an image using a specially developed scanning tunneling microscope (STM).[1] That image provided dramatic visual confirmation of the d-wave nature of the electron pairing state in such materials (see the cover of this issue).

> Researchers in Berkeley and Tokyo have demonstrated the great potential of a scanning tunneling microscope for studying the behavior of superconductors on an atomic scale.

With this result, the Berkeley and Tokyo collaborators, led by J. C. Séamus Davis and Shin-ichi Uchida, respectively, have demonstrated the unique potential of STMs for further explorations of the superconducting state at the atomic level. The new research capability is welcomed with enthusiasm by a number of theorists who have long held that one can learn a lot by studying how intruders such as zinc atoms can perturb the superconducting wave function.

The false-color image on the cover shows the density of electronic states around a single zinc atom sitting at the site normally occupied by a copper atom in a bismuth-strontium-calcium-copper-oxide (BSCCO) superconductor. The zinc sits in the critical copper-oxide plane, where the supercurrents predominantly flow. The interaction of this intruder with the surrounding superconducting pairs leaves its imprint on the electronic states. Indeed, the new STM image seems to reflect the symmetry of the high-T_c superconducting state. The clover-leaf lobes are what theorists predicted you'd see when the electrons are paired in an anisotropic state corresponding to two units of angular momentum (the d-wave state). If one could have produced such an image seven years ago, it might have quickly settled a controversy then raging over whether the electrons were paired in a d-wave state or in an s-wave state with zero angular momentum. (See PHYSICS TODAY, May 1993, page 17, and January 1996, page 19.) In 1993, Jeff Byers, Michael Flatté, and Douglas Scalapino, all then at the University of California, Santa Barbara, proposed that an STM measurement of the local density of states near impurity would provide the spatial information needed to determine the nature of the pairing state,[2] but the capability wasn't in place at the time.

Reacting to the new result from the Berkeley–Tokyo collaboration, Donald Eigler (IBM's Almaden Research Center) praised it as outstanding: "It's a visual confirmation of how the d-wave pairs interact with impurities and the role that impurities play in high-T_c superconductivity." Eigler, with Ali Yazdani and other IBM coworkers, has looked at impurities on the surfaces of conventional and high-T_c superconductors, but they did not pursue them in the same depth as the Berkeley–Tokyo collaboration.[3]



ZINC IMPURITY in a BSCCO superconductor. **(a)** Surface topography shows bismuth atoms in the top crystal plane. **(b)** Two layers down in the copper-oxide plane, a zinc atom is marked by a bright central peak in the differential conductance, together with secondary peaks. This zinc site lies below the bismuth atom marked by an X in the top panel. **(c)** Schematic diagram shows the a and b axes relative to the positions of copper (orange) and oxygen (green) atoms, to the bismuth lattice **(a)**, and to the lobes of the d-wave electron-pair wavefunction. Blue circles indicate positions of the peaks in the conductance **(b)**, with thickness of lines proportional to intensity. (Adapted from ref. 1.)

Years of development

The low-temperature (250 mK), high-vacuum STM built by the Berkeley group took years of development, largely in the hands of Shuheng Pan (now at Boston University) and Eric Hudson (now at NIST, Gaithersburg). The STM was designed specifically for experiments on high-temperature superconductors.[4] Pan, Hudson, Davis, and Kristine Lang set out to use this new STM to study vortices (work that continues) but along the way they spotted hints of impurity scattering of unknown origin.[4] The team decided to study known impurities placed at known sites. They settled on zinc, which should substitute for copper, because it was expected to give strong resonance scattering. They collaborated with Uchida and Hiroshi Eisaki of the University of Tokyo, who used their skill in growing high-quality copper-oxide crystals to infuse BSCCO with known concentrations of zinc atoms.

The surface of the BSCCO crystal is a plane of bismuth and oxygen atoms. A topographic scan, made by tunneling into this surface at right angles, revealed no sign of the zinc atoms, which are expected to be two layers below in the copper-oxide plane (see the top panel of the figure at left).

Davis and his coworkers then scanned the surface to measure the differential tunneling conductance at zero bias, which is proportional to the density of states available to electrons tunneling from the sample into the microscope's tip. In a conventional s-wave superconductor, there should be very few electronic states right at the Fermi surface: The differential conductance should be zero within a defined energy of the Fermi surface known as the superconducting energy gap. With the d-wave symmetry of high-T_c materials, that energy gap shrinks to zero at certain directions in momentum space—the nodal directions—but the density of states is still very small at the Fermi surface.

In the differential conductance image, most of the sample appeared black, corresponding to minimal conductance. But against this inky background shone a sprinkling of starlike spots. The high differential conductance at those stars indicated that the superconducting pairs had been broken and that a quasiparticle state had appeared in the center of the gap. The researchers were astounded at just how strong the differential conductance was: up to six times greater than the normal state conductance. All evidence suggested that the conductance peak could be ascribed to zinc atoms at the copper sites.

Seeing stars

The bright spots looked like many tiny crosses, all with the same orientation; a comparison of the spectroscopy with the topography confirmed that the arms of the crosses extended in the directions of the *a* and *b* crystallographic axes of the copper oxide planes (see the bottom panel of the figure on page 17). These axes are also the directions of the nodes in the d-wave superconducting pair wavefunctions. A closer look revealed that each cross also featured a weaker cross pattern, superimposed on the first but rotated by 45°. Both crosses are evident in the false-color image in the middle panel of the figure; the logarithmic scale of intensity there somewhat exaggerates the secondary crosses. Clearly, the density of states in the energy gap does not fall off sharply with distance away from the central impurity site but rather undulates, with side peaks at the sites of surrounding copper atoms.

The appearance of the star-shaped intensity pattern bears out the predictions of a number of theorists.[2,5,6] As one of those theorists, Alexander V. Balatsky (Los Alamos National Laboratory), explains it,[7] the anisotropic state at the zinc site is like a full glass of water, with the surrounding energy gaps playing the role of retaining walls. But water can leak out at the nodes, so the impurity state has tails in that direction.

Other details of the observations, such as the weaker, rotated crosses lying along the directions of the lobes, remain unexplained. These details and others likely to be uncovered by STM studies will continue to challenge theorists.

The Berkeley–Tokyo researchers are already studying the effects of a magnetic impurity—nickel—on the superconducting state; their results may have great relevance for theories that postulate a large role for antiferromagnetic correlations in the high-T_c pairing mechanism. The Berkeley group is also trying to build an STM that will operate at temperatures as low as 100 mK to enable measurements on strontium ruthenate, an unconventional superconductor (with T_c of only 1K) whose pairing state—strongly suspected to be p-wave—is still not convincingly established.

Barbara Goss Levi

References

1. S. H. Pan, E. W. Hudson, K. M. Lang, H. Eisaki, S. Uchida, J. C. Davis, Nature **403**, 746 (2000).
2. J. M. Byers, M. E. Flatté, D. J. Scalapino, Phys. Rev. Lett. **71**, 3363 (1993).
3. A. Yazdani, B. A. Jones, C. P. Luz, M. F. Crommie, D. M. Eigler, Science **275**, 1767 (1997). A. Yazdani, C. M. Howald, C. P. Lutz, A. Kapitulnik, D. M. Eigler, Phys. Rev. Lett. **83**, 176 (1999).
4. E. W. Hudson, S. H. Pan, A. K. Gupta, K.-W. Ng, J. C. Davis, Science **285**, 88 (1999).
5. A. V. Balatsky, M. I. Salkola, A. Rosengren, Phys. Rev. B **51**, 15547 (1995). M. I. Salkola, A. V. Balatsky, J. R. Schrieffer, Phys. Rev. B **55**, 12648 (1997).
6. M. I. Salkola, A. V. Balatsky, D. J. Scalapino, Phys. Rev. Lett. **77**, 1841 (1996).
7. A. V. Balatsky, Nature **403**, 717 (2000).

Experiments Reveal How Heat Is Mixed into Cold Dense Water in the Abyssal Ocean

By tracing the diffusion of a dye, researchers have found suggestive evidence that the moon promotes the flow of heat in the deep ocean.

If the world's oceans relied only on molecular diffusion and smooth laminar flow to spread the Sun's heat, they'd consist of a thin Sun-warmed layer atop a mass of icy water. But other transport mechanisms are at work. In the North Atlantic, for instance, wind-driven currents push warm water from the Caribbean to the Arctic, where it cools, sinks, and flows back southward. And throughout its journey, the seawater is swirled and agitated by continent-sized gyres and centimeter-sized turbulent eddies.

Determining exactly how these mechanisms work is important for more than just solving ocean dynamics. The transport of heat in the oceans is one of the key ingredients and among the largest sources of uncertainty in the complex computer programs (known as global circulation models) that are developed to investigate global warming. The better we understand ocean heat transport, the more confidently we can predict future climates.

For one heat transport mechanism—turbulent mixing in the deep ocean—the uncertainty has just been reduced. Reporting in a recent issue of *Nature*,[1] James Ledwell and his colleagues from Woods Hole Oceanographic Institution describe measurements of turbulent mixing at depths of 3500–5000 m off the east coast of Brazil. Their results can explain why deep water leaving the Brazil basin northward is warmer and lighter than water entering the basin from the south.

To determine the degree of turbulent mixing, the Woods Hole team measured two related quantities: the turbulence-enhanced diffusion of a chemical tracer and what oceanographers call microstructure—centimeter-scale turbulent fluctuations.

The tracer release experiments began four years ago when the team set sail in the *RV Seward Johnson* from Rio de Janiero to a point above the western flank of the Mid-Atlantic Ridge, the underwater mountain range that separates the South American and African continental plates. Once the team reached their destination, at 22° N, 18° W, they submerged a device to a depth of 4000 m and