

“and that limited our statistics. But in July we ran with 57 crystals, and we hope the new data will confirm the bands and their origin.” Even in its unfinished state, Gammasphere is much more powerful than the previous generation of detectors, which had only a 1–2% chance of recording a given gamma. They almost never saw more than two gammas in coincidence. With the overwhelming background of gammas from other processes, multigamma coincidences are crucial to the detection of hyperdeformation spectra.

Europe’s answer to Gammasphere,

the Eurogam II detector in Strasbourg, has joined the search for hyperdeformed nuclei. But picket-fence spectra, by measuring moments of inertia, can provide only indirect proof of hyperdeformation. The ultimate confirmation must await lifetime measurements of these femtosecond states, from which one can determine their quadrupole deformations.

David Ward, whose Chalk River group was the first to present evidence for nuclear spins of $90\hbar$ and above, points out a provocative puzzle: “If you think of the colliding nuclei in these experiments as billiard balls,” he told us,

“then the maximum impact parameter can’t get you anywhere near $90\hbar$.” So, in addition to worrying about fission, if the spins really are that high, one may have to invoke novel tidal forces that elongate the nuclei just as they are about to collide.

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STM Gets to the Core of the Matter in a High- T_c Superconductor

Researchers at the University of Geneva have succeeded in applying scanning tunneling microscopy to one type of high- T_c superconductor, opening the door to further study of the vortex cores.

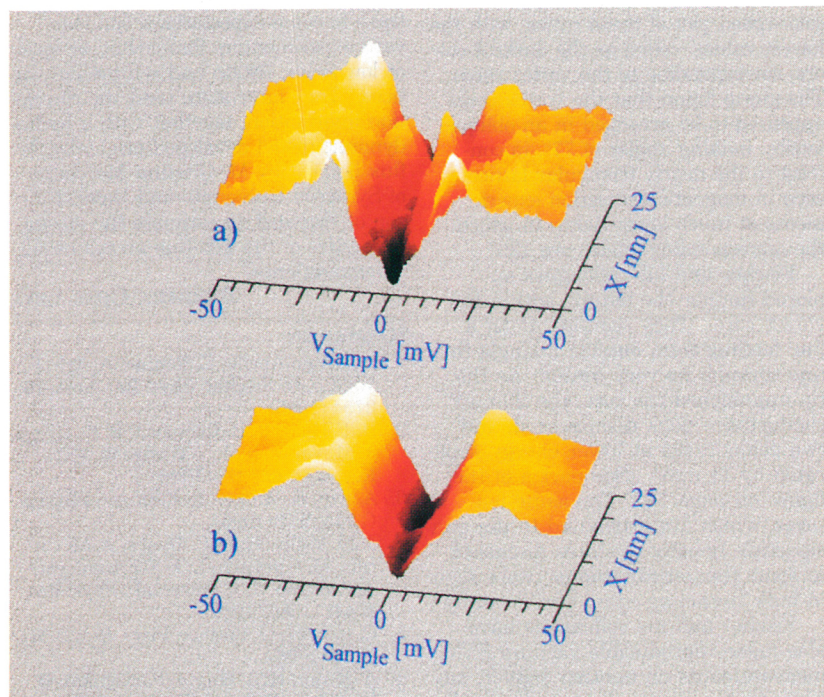
Since the 1986 discovery of high-temperature superconductors, researchers have been struggling to understand the nature of the magnetic flux lines that thread through these copper-oxide materials when the field is above a few tens of gauss. The flux lines take the form of vortices,

swirling supercurrents that confine the magnetic field to a cylindrical region around a quiescent center. Understanding them is more than an academic exercise: Motion of the vortices, when pushed by a high enough current, introduces resistivity and limits the long-sought high-field applications. (See PHYSICS TODAY, October 1992, page 17.)

You don’t actually have to see the vortices to learn about them, as we know from the very productive studies with such techniques as neutron diffraction. Nevertheless it’s useful to see real-space pictures of the vortices, which display visually the regular triangular lattices that form under certain conditions or the glasslike state they manifest under others. One method for producing such visual images is the magnetic decoration technique, in which tiny iron particles cluster around points of high magnetic field. Yet another technique—scanning tunneling microscopy—has now been demonstrated by a group led by Oystein Fischer at the University of Geneva in Switzerland to map the vortices of one of the most widely studied high- T_c materials, yttrium barium copper oxide (known as YBCO).¹ The results raise hopes that this technique can provide a new kind of information about the vortex lattices and especially about the vortex cores.

Electronic signature

The information provided by scanning tunneling microscopy is different from that available by other direct-imaging techniques such as magnetic decoration, scanning SQUID microscopy, Lorentz microscopy or scanning Hall probe microscopy. Rather than directly mapping the magnetic field, STM measures the current, or the



DIFFERENTIAL CONDUCTANCE SPECTRA measured by scanning tunneling microscopy on the surface of a YBCO crystal in 6 T. The conductance measures the electronic density of states. It is plotted here as a function both of voltage and of distance X along a line on the crystal surface. **a:** Conductance spectrum along a line that passes through a vortex. (The vortex core lies at the midpoint of the line.) **b:** Spectrum along a line between vortices. Going from dark red to white, one ranges from low to high values of differential conductance. The peaks seen around 20 mV remain constant between vortices (**b**), but they disappear at the core (**a**); they are replaced there by conductance peaks separated by 11 mV. (Adapted from reference 1.)

flow of electrons tunneling from the instrument tip into the surface being scanned. The current is higher when there are more states into which electrons can tunnel. Hence the STM maps the local electronic density of states within the superconductor—a quantity that can give insights into the still contested nature of the electron-pair symmetry.

STM samples the relatively short coherence length defining the vortex core, where the density of states is high, so it can be applied at high fields; indeed it works best there. The Geneva measurements were done at 4.2 K, in a field of 6 tesla. They thus complement the imaging techniques that directly track the field, which are limited to fields below a few tens of a mT, because as the field gets stronger the flux lines start to merge.

Secrets of success

Harald Hess and his colleagues at AT&T Bell Laboratories in Murray Hill, New Jersey, had first applied scanning tunneling microscopy to image vortices in conventional superconductors² (see *PHYSICS TODAY*, June 1990, page 17), but neither Hess nor many others had succeeded in extending this technique to its higher- T_c cousins. Materials problems with the copper oxides often make it hard to get the high-quality surfaces required for reproducible tunneling. The Geneva group succeeded, according to Christophe Renner and Ivan Maggio-Aprile, who did the STM measurements, in part because of the very pure single crystals of YBCO that their colleagues Andreas Erb and Eric Walker have been able to grow in barium zirconium oxide crucibles³ they developed; these crucibles do not react with any of the highly reactive melts used as solvents. The Geneva experimenters have also made many small improvements so that their STM can operate stably, at high fields and in a very clean environment. It helped, Renner told *PHYSICS TODAY*, to operate at a high field, so that the vortex cores were clustered in a smaller area and required less imaging time.

To determine the vortex pattern, Maggio-Aprile and Renner scanned the STM tip at a constant distance above the sample surface and determined the differential conductance (dI/dV), which is a measure of the density of states. When plotted as a function of voltage, this quantity behaved differently from that of a conventional, low- T_c superconductor but consistent with the conductance spectrum seen in earlier planar tunnel

junction measurements on YBCO.⁴ At zero field, the spectrum measured by the Geneva group had a dip below the superconducting energy gap, but it did not go to zero as in a conventional superconductor. It showed a gaplike structure with a conductance peak around 20 milli-electron volts—and a smaller feature at 27 meV. The spectrum was the same at all points on a sample, as one might expect for a homogeneous superconductor. (See part b of the figure on page 19. The voltage in the figure is numerically equal to the electron energy in meV.)

Once the field was applied, however, the Geneva experimenters found a different spectrum at certain points—points that they interpret as being in or near the core of a vortex. In these regions the 20-meV and 27-meV conductance peaks shrank, and two peaks developed below the 20-meV gap.

The difference in the conductance spectrum in the vicinity of flux lines provided a way to map the vortices. The Geneva researchers measured the ratio of the differential conductance at 20 meV to that close to 0 meV at each point on the surface. They then generated a color-coded plot of these ratios, with the lowest values (coded as the darkest colors) corresponding to the vortex cores. The group found that the vortex cores appeared to be arranged in an oblique lattice, making angles of 77°, in contrast to the nearly triangular lattice seen in magnetic decoration experiments at much lower fields, in which the corresponding angles are 120°.

Fischer and his colleagues explored further the details within the vortex core. They scanned along a line leading from outside a single flux line through its very center. As the tip approached the core, the 20-meV conductance peak disappeared, and two peaks arose at lower energy, separated by 11 meV. (See part a of the figure on page 19.) The same features, which are attributed to the quasiparticle density of states discussed in some theoretical studies, were seen in bulk tunneling in an earlier study.⁴

Fischer and his colleagues have also made reproducible vacuum STM measurements on another high- T_c superconductor, bismuth strontium calcium copper oxide (BSCCO), but they have not seen the expected signatures of the vortex cores.⁵

Other techniques

Last March researchers demonstrated yet another method for studying high- T_c vortices—magnetic force microscopy. A group from the University of Basel in Switzerland, led by Hans J.

Hug, together with Praveen Chaudhari of the IBM Corp's Thomas J. Watson Research Center in Yorktown Heights, New York, reported using this method to image successfully the vortices in thin films of YBCO.⁶ Magnetic force microscopy is much like atomic force microscopy except that the tip responds to a magnetic rather than a contact force.

Another group of researchers, this one at Harvard University, has built upon the traditional magnetic decoration technique to gain a new capability, one that allows the group to ascertain whether the vortex lattice at a sample surface has anything to do with the vortex lattice structure in the bulk of the material.⁷ The Harvard team, led by Charles Lieber, decorated opposite sides of a BSCCO crystal simultaneously and looked for correlations between the lines that enter on one side and those that emerge on the other. The patterns of lines make it possible to determine if the vortices are columnlike structures, passing as lines through the sample, or if the vortices have a predominantly two-dimensional structure, looking like so many pancakes lying in each of the copper-oxide planes. Contrary to some expectations, the Harvard experimenters found that, at least at low fields, BSCCO had columnlike vortices. They have since used the correlation information, together with a hydrodynamic model developed originally for flux liquids⁸ by M. Cristina Marchetti of Syracuse University and David Nelson of Harvard, to estimate the elastic properties of the flux-line arrays based on experiments.⁹

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