virus attacks can certainly infect a communications network, causing router congestion that leads to denial-of-service errors; these behave in a way analogous to overloading, though no nodes are really killed.

The extent to which some nodes are more vulnerable than others is controversial. Many network theorists argue that the internet is scale-free on the level of autonomous domains (university.edu domains, or huge service providers like AOL or MCI). But AT&T network researcher Walter Willinger cautions that this scaling perspective is a red herring. "Technologically, routers in the core of the network just cannot accommodate large numbers of high-bandwidth connections." The core networks of large service providers really consist of a large number of high capacity routers, for instance, that may be widely spread around the world. "It's hard to imagine taking out a node . . . by effectively attacking all the core routers as a group" he says.

Motter's method of cascade control does not depend on any particular network structure or details of the flow. The task of catering to specific requirements still remains. In fact, he is now adapting his model to the much different system of social networks, where each node—a person—can influence just a few others or up to tens of thousands (see PHYSICS TODAY, September 1998, page 17). Imagine that a rumor starts somehow and you'd like to shut down its spread. The idea would be to prevent a transition between a phase in which few are persuaded and one in which many are, without fracturing the social network. The algorithm for such an action might be one that politicians and their spin doctors find useful.

Mark Wilson

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New Experiments Highlight Universal Behavior in Copper Oxide Superconductors

Similar patterns of spin fluctuations and charge ordering in different compounds suggests that these features are intrinsic to the cuprates.

Since 1986, when lanthanum barium copper oxide (LBCO) was found to superconduct above 30 K, many other such high-critical-temperature (high-T_c) superconductors have been found, all of them copper oxides having layered structures. The superconductivity appears to arise from the planes of copper and oxygen atoms common to these compounds.

The undoped parents of all high-T_c superconductors have one valence electron per copper atom. The ground state is an antiferromagnetic insulator, in which the spin of each electron is aligned opposite that of its neighbors. Once the compound is sufficiently doped with holes or electrons, it goes superconducting below T_c, and the electrons move in coherent pairs throughout the sample. Just how the material makes the transition between these very disparate states has been the subject of intense study.

Of particular interest is the nature of any spin or charge ordering, either in the fully superconducting state or in the underdoped state. When the material is underdoped but above T_c, it's in the so called pseudogap region, where the material is in some intermediate state between antiferromagnetism and superconductivity. Do the charges, for example, arrange themselves in some regular pattern? Is that pattern stripelike, or more like a checkerboard? Probing the charge or spin structure might elucidate the underlying order and perhaps answer whether magnetic order competes with superconductivity or is essential to it.

The latest revelations about spin or charge order have come largely from complementary types of experiments. Scanning tunneling microscopy (STM) measures the static density of electrons, thereby giving a satisfying visual image of how the charge is ordered. But it can only see the surface. By contrast, neutron scattering is sensitive to the spins and not the charge. It's a probe of the dynamical spin excitations throughout the bulk of a sample.

Ideally one would like to apply both methods to the same material. Such attempts have been largely stymied, however, because some materials lend themselves more readily to one type of measurement than to another. It's hard to tell whether the data reflect individual or universal properties.

STM has primarily probed the surface charge order in crystals of bismuth strontium calcium copper oxide ($Bi_2Sr_2CaCu_2O_{8+\delta}$, or BSCCO for short) because those crystals cleave so cleanly. Neutron scattering studies have been done on yttrium barium copper oxide ($YBa_2Cu_3O_{6+x}$, or YBCO for short) and on lanthanum strontium copper oxide ($La_{2-x}Sr_xCuO_4$, or LSCO), which one can grow in sufficiently large crystals. Neutron scattering has been hard to do on BSCCO because of the small size of available single crystals, and STM studies of YBCO have been thwarted by the lack of a clean surface.

Broadened perspectives

A spate of experiments reported in the past six months has now enriched the picture regarding charge and spin order. Some of the experiments were done on materials that had not previously been available, and some used new or improved techniques. As a result, patterns previously seen in one member of the copper oxide family are showing up in other compounds, or under different conditions.

In the case of STM studies, evidence has been accumulating in the past few years for a checkerboard-like pattern of electronic modulation in BSCCO.[1–3] The most recent such evidence comes from an experiment done earlier this year[4] that found charge order in the pseudogap region by probing an underdoped sample above T_c. Last month, as seen on the cover of this issue, another experiment revealed[5] static checkerboard charge order in a very different cuprate, known as sodium-doped calcium copper oxychloride ($Ca_{2-x}Na_xCuO_2Cl_2$, or Na-CCOC). In both the new STM studies, the charge order was found under conditions that suppress superconductivity.

As for neutron scattering experiments, recent work has shown, contrary to naive expectations, that the energy dependence of the magnetic excitations in superconducting YBCO is similar to that of a member of the lanthanum copper oxide family ($La_{1.875}Ba_{0.125}CuO_4$) that is not superconducting but does have a stripelike arrangement of spins and charges.[6,7] Other experiments[8,9] concur on the behavior of the spin excitations in copper oxide compounds, although researchers disagree on the finer details.

The STM and neutron scattering experiments have broadened our knowledge of high-T_c materials, but it's not clear how their separate findings are related to one other. Only

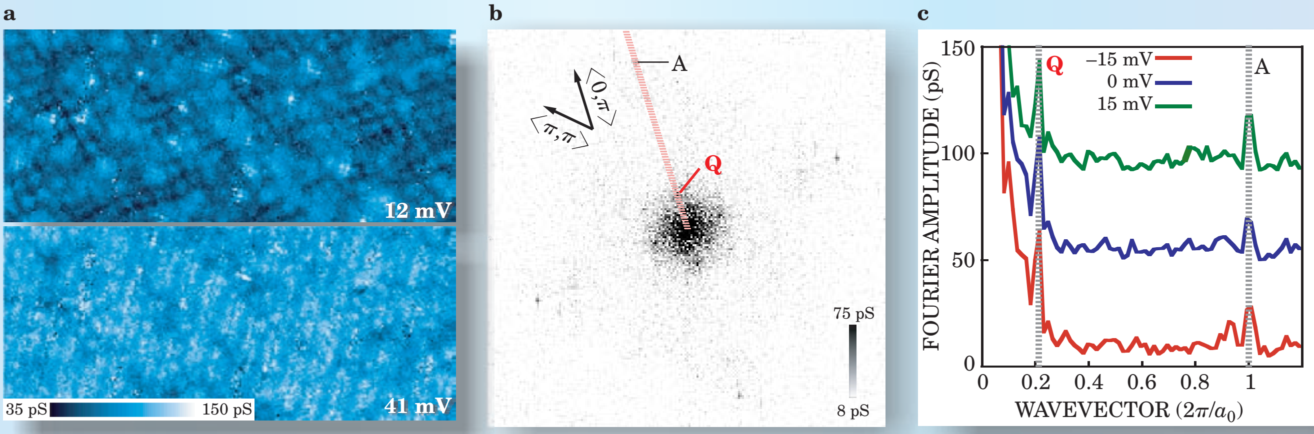

Figure 1. Charge order in underdoped BSCCO above T_c, as determined by scanning tunneling microscopy. **(a)** Conductance maps. Below the peudogap energy, at a tip-to-surface bias of 12 mV, one can see a pattern of charge order amid an inhomogenous background. Above it, at 41 mV, one sees modulations due to atoms and a known lattice distortion. The field of view is 45 nm by 19.5 nm. **(b)** Fourier transform of conductance map reveals four points (one of which is labelled A) associated with atomic sites and four points (Q) due to charge ordering. The copper– oxygen bonds are oriented along the <0 , π> direction. **(c)** Wavevectors at Q and at A show no change with bias voltage. (Adapted from ref. 4.)

when several different techniques are brought to bear on the same material will researchers get some insight into how the spin and charge structures influence one other.

Probing the charge order

In STM, one scans a conducting tip over a surface while modulating the tip-to-surface voltage. The instrument measures the tunneling conductance—that is, the change in tunneling current with voltage—as a function of position. Such conductance measurements map the electronic density of states over the surface.

To bring out any periodic structures in the charge density, researchers do a fast Fourier transform of their data. The output is a set of peaks at wavevectors that correspond to repeating patterns in the data.

Using this technique, researchers have found regular patterns of electronic density of states in BSCCO under a variety of conditions.

Several years ago Aharon Kapitulnik and his group at Stanford University reported seeing charge modulations of roughly four lattice spacings in optimally doped BSCCO above and below T_c, although the modulations seen below T_c were quite weak.[3] In another study of BSCCO samples ranging from slightly underdoped to slightly overdoped, Séamus Davis (now at Cornell University) and collaborators from the University of California, Berkeley, and the University of Tokyo concluded in 2002 that the spatial modulations seen in their data below T_c could all be attributed to interference from the elastic scattering of quasiparticles due to disorder.[2]

There's growing evidence that charge order is present when superconductivity is weakened. In another experiment also done in 2002, Davis and coworkers found a checkerboard modulation of electronic density in slightly overdoped BSCCO near the core of a magnetic flux line—where the superconductivity had been destroyed.[1] The charge modulations were characterized approximately by a wavevector equivalent to four lattice spacings, or $4a_0$. (See PHYSICS TODAY, February 2002, page 14.)

This March, Ali Yazdani and his coworkers at the University of Illinois at Urbana-Champaign, and the Central Research Institute of Electric Power Industry in Tokyo, Japan, looked for charge order in the pseudogap region of BSSCO.[4] That region poses a big mystery: The electrons there appear somehow poised to enter the superconducting state but have not yet condensed into coherent pairs.

The experiment was a challenge, as it had to be conducted at a much higher temperature than most STM measurements. The group took data at 100 K—above the 80-K T_c of the slightly underdoped sample.[4] From the data they collected, seen in figure 1, the Illinois–Tokyo experimenters zeroed in on the four peaks arranged along the Cu–O directions at periodicities of $4.7a_0$. Yazdani and his group have shown that these peaks are not consistent with quasiparticle interference but instead represent a static modulation such as one might expect from charge ordering. The charge modulation is seen only at energies within the pseudogap.

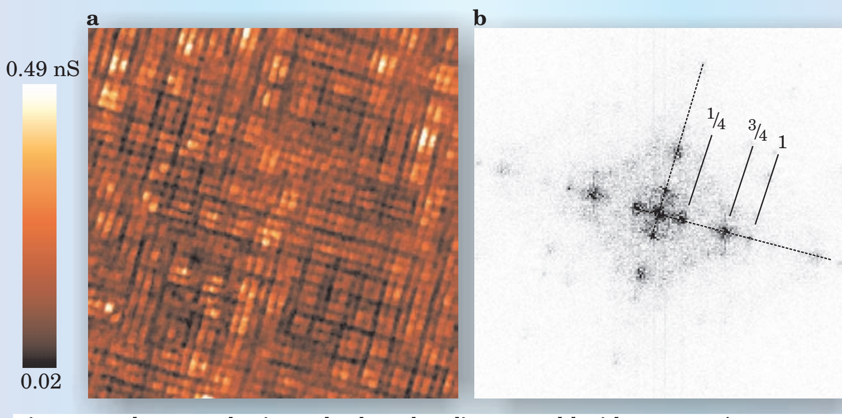

Figure 2. Charge order in underdoped sodium oxychloride (a) Conductance map measured at 8 mV. Field of view is 20 by 20 nm. **(b)** Fast Fourier transform reveals peaks at a wavevector of 1, attributed to the atomic lattice, as well as peaks of unexplained origin at 3/4 and 1/4. Experimenters believe the wavevector of 1/4 reflects a $4a_0 \times 4a_0$ checkerboard pattern of charge. Wavevectors are measured in units of $2\pi/a_0$. (Adapted from ref. 5.)

Sodium oxychloride

BSCCO is doped by the addition of oxygen atoms, which can distort the lattice and introduce some wavevectors that complicate interpretation of STM data. Davis teamed with Hidenori Takagi of RIKEN and the University of Tokyo to apply STM to a copper oxide that did not have such distortions and that was stable even when greatly underdoped. Davis credits Takagi for pioneering the study of Na-CCOC and for preparing the samples that his team used. Team members came from RIKEN's Magnetic Materials Laboratory in Wako, Japan; Cornell; the University of California, Berkeley; the Lawrence Berkeley National Laboratory; the University of Tokyo; and Kyoto University.[5]

That collaboration studied samples of Na-CCOC whose doping varied from from $x = 0.08$ to 0.12. Figure 2 shows representative results taken with a bias voltage of 8 mV and at a temperature of 100 mK. The experimenters found that the wavevectors are independent of energy, up to 100 mV, and independent of the doping level.

To argue the relevance of their Na-CCOC results to other copper oxides, Davis, Takagi, and colleagues point out that a curve of the tunneling conductance versus tip bias is virtually the same for underdoped BSCCO as it is for Na-CCOC. Philip Anderson and Nai-Phuan Ong of Princeton University have recently calculated the shape of the conductance curve.[10]

Despite its virtues, Na-CCOC is not nearly as well characterized as the experimental warhorse, BSCCO. Such characterization might help further establish how Na-CCOC relates to other cuprates and the extent to which a measurement on its surface reflects what's happening in the bulk.

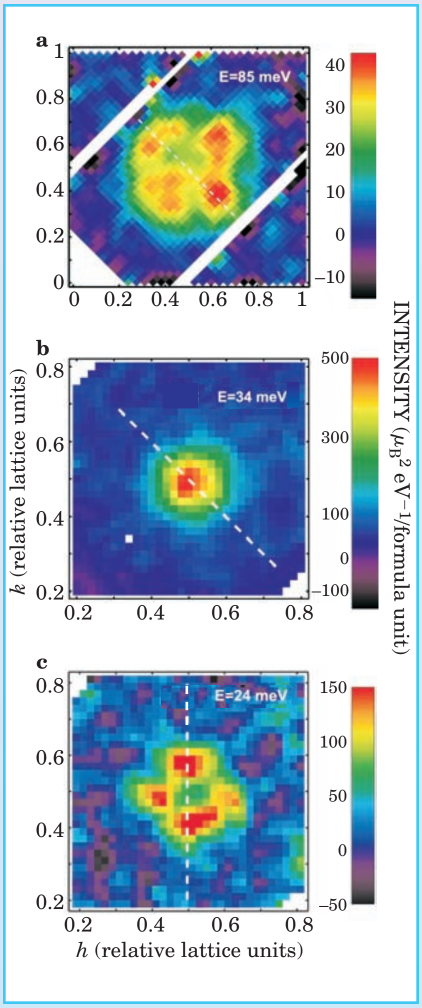

Figure 3. Superconducting YBCO. The neutron scattering diffraction patterns at three energies follow the same trend as in a stripe-ordered compound, LBCO, as seen in figure 4. The square pattern of peaks at 24 meV **(c)** coalesce toward the center by 34 meV **(b)**, then spread outward again by 66 meV **(a)**. (Adapted from ref. 6.)

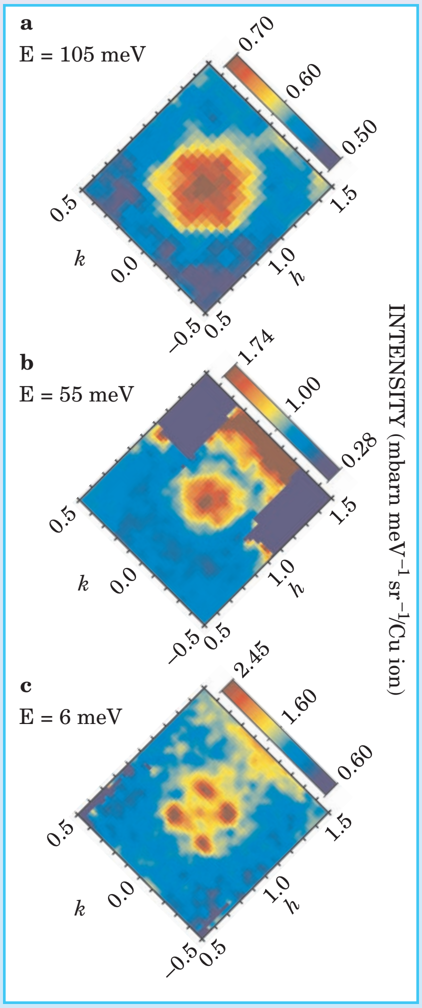

Figure 4. Stripe-ordered LBCO. Neutron scattering peaks seen at 6 meV **(c)** merge into a central peak by 55 meV **(b)** and then diffuse outward by 105 meV **(a)**, as in figure 3. These images have been rotated to facilitate comparison because the two experiments used different coordinate systems. (Adapted from ref. 7.)

Neutron scattering

Neutrons can scatter from the atomic nuclei or from the electronic spins on copper sites. A static but periodic arrangement of spins is detected by peaks in the spectrum of elastically scattered neutrons; dynamical spin fluctuations are registered as peaks in the inelastic spectrum.

Neutron scattering off lanthanum copper oxide, the antiferromagnetic parent of several of the high-T_c cuprates, produces a diffraction peak at what's called the superlattice wavevector in reciprocal space. It's centered at a wavevector of (½,½) in units of $2\pi/a_0$. When this compound is doped, the superlattice peak splits into four peaks in reciprocal space, each displaced by a distance δ along one of the orthogonal axes. This splitting reflects some additional ordering that is apparently modulating the antiferromagnetic correlations.

To understand how such peaks might arise, consider just one simple model for spin modulation: the organization of the copper oxide plane into linear stripes of segregated charges (holes) and spins (copper atoms), each two atoms wide. If all such stripes extend in the same direction, one would see two peaks on either side of the superlattice point. Because the alternating pattern of spin reverses every 4 lattice units, the modulated superlattice peaks would appear at (½ ± ⅛,½) or (½,½ ± ⅛), depending on the orientation of the stripe. Most cuprate crystals have equal numbers of planes with orthogonal stripe direction, so four peaks appear.

The most prominent feature of neutron scattering in YBCO is a strong resonance peak at the superlattice position (½,½). Some theorists think this resonance plays a large role in superconductivity.

Experimental groups have reported similar resonances in BSCCO[11] and doped thallium barium copper oxide.[12] Until this June, no one expected to see the resonance peak in stripe-ordered LBCO. That's when John Tranquada and coworkers from Brookhaven National Laboratory and Tohoku University published a paper reporting[7] a resonance in LBCO doped at x = ⅛. At that level, the superconductivity is anomalously suppressed and the material is known to have stripe order. Tranquada credits Tohoku's Masaki Fujita and Brookhaven's Genda Gu with growing large samples of LBCO, which is notoriously hard to dope.

The study of LBCO was published at the same time as a neutron scattering experiment on YBCO that looked at energies well above the resonance.[6] The two papers together show that the energy dependence of the diffraction patterns in YBCO and LBCO share some universal features. The data on YBCO was taken by researchers led by Herbert Mook of Oak Ridge National Laboratory. Team members hailed from Oak Ridge, the University of Tennessee, Knoxville, the Rutherford Appleton Laboratory (RAL) at Oxford, England, the University of Bristol, and the University of Missouri–Rolla. The studies of both YBCO and LBCO, made at high energies and at high momentum resolution, were made possible by the new MAPS time-of-flight spectrometer at the ISIS neutron spallation source at RAL.

Hourglass shape

Mook's and Tranquada's groups traced the incommensurate peaks seen in YBCO and LBCO as a function of energy transferred to the spin excitations. As shown in figures 3 and 4, the fourfold incommensurate peaks seen at low energies moved toward the center in momentum space as the energy increased, eventually merging into a single peak at ($\frac{1}{2}$,$\frac{1}{2}$) at the resonance energy. As the energy was raised still further, the peaks separated and moved out again. Plotting the wavevector, or momentum, versus energy yields a dispersion curve that is shaped like an hourglass.[13]

Disagreements remain over some of the details of what's been observed. For example, Tranquada, Mook, and their colleagues contend that the diffraction patterns seen above resonance in YBCO and LBCO are squares that have been rotated by 45° compared to the orientation seen below resonance. Bill Buyers of the National Research Council Canada at Chalk River believes the patterns are just as consistent with rings, like ones he and his collaborators have seen in underdoped YBCO.[9]

Recently Gabriel Aeppli of University College London and colleagues, working with a crystal of LSCO, have seen fully two-dimensional excitations, which disperse inward toward the resonance position.[8]

To explore whether the spin modulation is two dimensional or one, a group led by Bernhard Keimer of the Max Planck Institute for Solid State Research in Stuttgart, Germany, and by Philippe Gourges from the Laboratoire Léon Brillouin in Saclay, France, measured the neutron scattering from a crystal whose copper oxide planes were nearly all aligned in the same direction.[14] The diffraction pattern was a ring, although the intensity was stronger at two diametrically opposed points around the ring. The researchers concluded that the spin excitations were two dimensional.

Tranquada and company did a simple calculation to demonstrate that his group's data were consistent with what's predicted by a model of spin ladders, one form of interaction among linearly aligned spins. Subir Sachdev (Yale University), who has played with a variety of spin-ladder models, is surprised at how much even the relatively crude models get right. At the same time, Patrick Lee (MIT) says that the inward dispersion of the diffraction peaks as one lowers the energy below the resonance has been predicted by conventional Fermi-surface nesting calculations, while the outward dispersion above resonance is extremely broad and may be generic to spin liquids rather than to any specific ladder model. Clearly the debate will continue.

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