A complex picture. Composite MODIS satellite image of Whillans Ice Stream (upper right, flowing to lower right) and the adjacent Ridge BC or Ridge Whillans/C (left), feeding the Ross Ice Shelf (lower right). The slower flowing ridge appears smooth compared with the faster flowing ice stream. The former shear margin of Ice Stream C, which slowed greatly just over a century ago, is visible toward the lower left crossing the ridge onto the ice shelf and joins a former Whillans-Ice-Stream shear margin that now crosses a corner of the ridge. The slowdown of C and narrowing of Whillans Ice Stream are consistent with the reduced discharge and net thickening of the Siple Coast region reported in (*1*). However, the dark regions (crevasses and rifts) in the lower center, near where the ice stream, ridge, and ice shelf meet, are probably linked to a widening of the ice stream back into the ridge (*6*). In addition, ice rise "a" (upper right corner) is apparently a piece of slow-moving ridge ice incorporated into and moving with the high-speed ice stream (*5*). The widening of Whillans Ice Stream and incorporation of ice rise "a" show that changes in the region can involve speed up and thinning as well as slowdown and thickening.

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maximum (*7*), researchers turned on their instruments just in time to catch the stabilization or readvance of the ice sheet.

Earlier work by Tulaczyk *et al.* (*8*) may even explain why. Basal melting occurs—and allows faster motion—where the heat from Earth's interior and from flow friction exceeds the heat conducted into the ice. The thinning that may have accompanied postglacial retreat of the ice sheet would have moved cold surface ice closer to the bed, increasing basal heat loss and thus favoring basal freezing and ice-stream slowdown.

Lest coastal property owners become too optimistic, however, it is important to remember how short the instrumental record is and how poorly characterized the natural variability. Sedimentary records indicate that ice streams have paused or even readvanced during the retreat since the last ice age (*9*). And observations from boreholes through ice streams suggest the presence of excess basal water supplied by melting beneath thicker ice inland (*10*). Latent heat from freezing of this water can warm the cold ice without freezing the ice streams to their beds (*11*).

Joughin and Tulaczyk (*1*) also highlight the great complexity of the system. They studied ice streams that feed the floating Ross Ice Shelf and that are slightly impeded by friction produced where the ice shelf runs aground (*12*). Reduced ice-stream flow into the ice shelf may allow it to thin and float free of the impeding grounding points, perhaps rejuvenating the ice streams and thus the ice shelf. Failure of this complex feedback path may lead to ice-shelf shrinkage or loss, with implications for formation of oceanic deep waters and thus for large-scale climate.

Access logistics and contrasting ice-stream styles have focused research on the Ross (*1*) and Filchner/Ronne (*13*) drainages. Yet the logistically difficult Pine Island Bay drainage is probably the most likely of the three major basins to experience the onset of dramatic ice-sheet changes (*14*). Here, thick, fast-moving ice discharges into relatively warm ocean waters without the protection of a large ice shelf. Speed up of ice flow and thinning are indeed occurring (*15*) but it remains unknown whether these changes will persist in the long term. Fortunately, the research tools developed by Joughin and Tulaczyk (*1*) and other researchers should allow rapid progress.

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PERSPECTIVES: SUPERCONDUCTIVITY

Tuning Order in Cuprate Superconductors

Subir Sachdev and Shou-Cheng Zhang

In 1986, superconductivity—the ability to transport electrical current without substantial resistance—was discovered in cuprate compounds. These materials have fascinated physicists ever since, in part because of the high critical temperatures (T_c's) below which superconductivity is present and the consequent promise of technological applications. However, cuprate superconductivity also raises fundamental questions about the collective quantum properties of electrons that are confined to a lattice and interact with each other (the "correlated electrons" problem). On page 466 of this issue, Hoffman *et al.* (*1*) report an innovative scanning tunneling microscopy (STM) study that should help answer some of these questions.

All discussions of cuprates begin with the compound La_2CuO_4. Its valence electrons reside on some of the 3d orbitals of the Cu ions, which are arranged in layers. In each layer, the Cu ions are located on the vertices of a square lattice, and the ability of electrons to hop between successive layers is strongly suppressed by the negligible interlayer overlap of the 3d orbitals. La_2CuO_4 is an insulator; its inability to transmit electrical current within a layer is a result of the Coulomb repulsion

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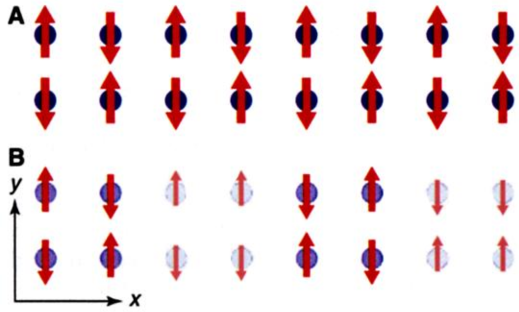


Electron spin configurations on the square lattice of Cu ions. The arrows represent the direction and magnitude of the average spin moment. Blue shading represents the average electron charge density on each Cu site. (**A**) Néel state in the insulator at $\delta = 0$. The spins oscillate with a period of two lattice spacings in the x and y directions. (**B**) Density wave at a moderate value of δ. A single period of eight lattice spacings is shown along the x direction; the period along the y direction remains at two lattice spacings. Unlike (A), the magnitude of the spin moment, and not just its orientation, changes from site to site; we can also expect (*5*) a corresponding modulation of the charge density on each site. The wavelength of the charge density wave is half that of the spin density wave in both directions.

between the electrons, which localizes them on the Cu sites. Moreover, the spins of the electrons are oriented up and down in a checkerboard pattern (see panel A, first figure): This quantum phase (or state) is called an insulator with "Néel" or antiferromagnetic order.

If we keep the material at zero temperature and tune another parameter, such as the charge carrier concentration or the magnetic field, we can explore the different quantum states of the system. For example, the properties of La_2CuO_4 change when mobile charge carriers are introduced into the insulating Néel state by chemical doping. In $La_{2-\delta}Sr_\delta CuO_4$, a fraction δ of the electrons is removed from the square lattice. The motion of the resulting holes is no longer impeded by Coulomb interactions, and for $\delta >$ 0.05, the quantum state of the electrons is a superconductor. This superconductivity is present at all temperatures below T_c.

For $\delta > 0.2$ and at low temperatures, the cuprates appear to be qualitatively well described by the well-established Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity. In this theory, the mobile electrons form pairs that condense into a quantum state extending across the entire system. A gentle spatial deformation of this state can set up a "superflow" of pairs, leading to the phenomenon of superconductivity. However, the internal wave function of the electron pairs has an unconventional structure in the cuprates: The spins of the electrons are oriented so that the total spin of the pair is zero, but their orbital motion around each other is described by a wave function with d-wave symmetry. In most low-T_c superconductors studied before 1986, this wave function has an s-wave symmetry.

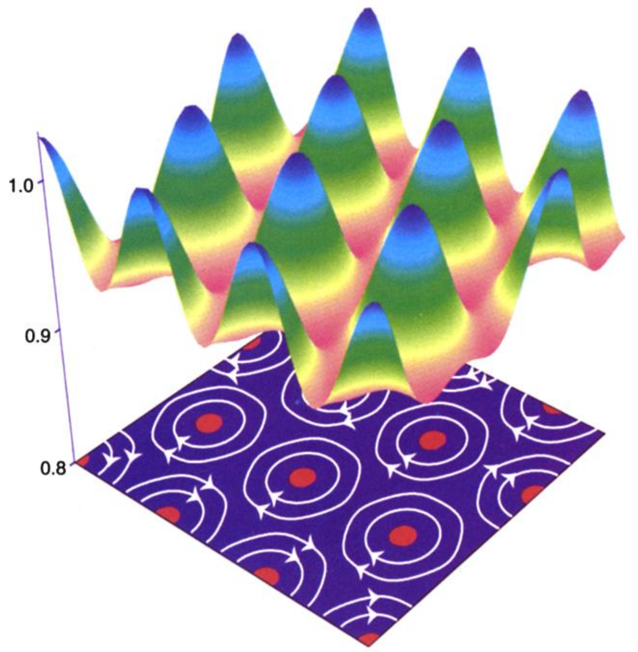
During the last decade, the debate has centered on the nature of the quantum state of the cuprates at intermediate δ—between the well-understood limits of the Néel insulator at $\delta = 0$ and the BCS superconductor at larger δ. Many candidate states have been proposed. A useful way of characterizing them is in terms of different types of "order," usually associated with breaking the symmetry of the electronic ground state. For example, the Néel state breaks the symmetry of spin rotations and lattice transitions, and the superconductor breaks the symmetry of charge conservation.

First, the order may be a spatial modulation of the local spin or charge density (*2–5*). The simplest example is the Néel state found in the insulator at $\delta = 0$ (see panel A, first figure). This state can be viewed as a wave in the spin density, with a wavelength of two lattice spacings in the x and y directions. At nonzero δ, the wavelength of the spin density wave changes; the orientation and period of this more complex wave (see panel B, first figure) are described by a δ-dependent wave vector $\mathbf{K}$. A charge density wave accompanies most such spin density waves, with a wave vector of $2\mathbf{K}$ (*6*). These spin and/or charge density waves are present at small δ but eventually vanish at one or more quantum critical points, leading to full restoration of invariance under spin rotations and lattice translations.

In this picture, the order associated with superconductivity and with spin and charge densities should provide the foundation of a theory of the cuprates at all δ. At low δ, the spin density wave order dominates, resulting in a Néel state; at high δ, the order associated with superconductivity dominates; and at intermediate δ, the two compete.

Second, the order may be associated with the fractionalization of the electron (*7*, *8*). In certain theoretically proposed quantum states, the electron falls apart into independent elementary excitations, which carry its spin and charge (such states need not break any symmetry). Experimental tests for fractionalization have, however, not yielded a positive signature so far (*9*, *10*). A third set of proposals (*11–13*) focuses on a rather unconventional order linked with the spontaneous appearance of circulating electrical currents and an associated breaking of time-reversal symmetry.

Given the distinct signatures of these proposals, one might expect that experiments can resolve the situation quite easily. However, the difficulty of smoothly varying the value of δ while maintaining sample quality and avoiding extraneous chemical effects has hampered progress. A recent set of experiments (*14–18*), especially those reported by Hoffman *et al.* (*1*), has led to a breakthrough. These experiments show that it is possible to "turn a knob" other than δ to tune the properties of the cuprate superconductors. The



Magnetic field penetration of a superconductor and associated order. The superconducting order is suppressed at the cores of the vortices (red dots). Superconducting currents (white loops) circulate around the vortex cores. Experiment and theory indicate that the spin and charge orders depicted in panel B in the first figure can exist in the vortex state. The colored surface shows the envelope of this order parameter, superimposed on the vortex lattice. This type of order can be static or dynamically fluctuating depending on the level of doping and the magnetic field. The spacing between the vortex cores is proportional to the inverse square root of the applied magnetic field and is typically about 50 times the spacing of the lattice in the first figure.

"knob" is a magnetic field applied perpendicular to the layers. Detailed dynamic and spatial information on the evolution of the electron correlations as a function of the applied field has been obtained. These data should help solve the mystery of the cuprates.

Hoffman *et al.* studied a cuprate superconductor in an applied magnetic field by a novel STM technology of atomically registered spectroscopic mapping. The field induces vortices in the superconducting order. Around each of the vortices, there is a superflow of electron pairs. An innovative analysis of their large amounts of STM data, with very high spatial and energy resolution, enables Hoffman *et al.* to factor out the substantial noise generated by chemical impurities introduced through doping and to test directly for orders other than superconductivity.

Theoretical studies pointed out (*5*, *19*) that the suppression of superconductivity in the vortex cores should induce local magnetic order. This repulsion between the superconducting and magnetic orders also appears in theories of magnetic quantum phase transitions in the superconductor (*4*, *5*, *20*). Combining these past works with insights gained from neutron scattering experiments by Aeppli and co-workers (*15*, *21*), Demler *et al.* (*22*) have pointed out that dynamic spin density wave correlations (like those in panel B, first figure) should be enhanced in the regions of superflow that surround the much smaller vortex cores. Static order in the associated charge density wave has been proposed (*23*), in coexistence with dynamic spin fluctuations and well-established superconductivity (see the second figure).

Consistent with these expectations, the STM observations show a clear modulation with a period of four lattice spacings in the electron density of states around the vortices, in regions that also display the characteristic signatures of electron pairing associated with superconductivity. Moreover, the wave vector of this ordering is 2**K**, where **K** is the wave vector for spin density wave ordering observed in neutron scattering (*15*) (albeit in a different cuprate superconductor). The observed field dependencies of the neutron scattering intensities (*15*, *17*, *18*) are also consistent with theoretical expectations (*19*, *22*).

These observations are compelling evidence that the order competing with superconductivity is the first of those discussed above: A slight suppression of superconductivity reveals a modulation in observables linked to the electron charge density. This coexistence region between superconductivity and the competing order should yield interesting new insights into the fundamental properties of cuprates. Similar modulations should be observable around other regions of the sample where the density waves can be pinned, for example, near impurities within the Cu plane.

The scope for further studies using the magnetic field as a tuning parameter is also wide. It should be possible to tune the cuprates to the vicinity of quantum phase transition(s) associated with spin and charge ordering. Similar studies can also be carried out in other correlated electron systems, including electron-doped cuprates, organic superconductors, and intermetallic compounds known as heavy-fermion materials.

The next challenge will be to use our improved understanding of the low-temperature properties of cuprate superconductors to formulate a theory of competing orders above T_c. Here many mysteries remain, particularly the microscopic origin of the "pseudogap" behavior, that is, the appearance of features characteristic of the energy gap of the superconducting state at temperatures well above T_c.

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PERSPECTIVES: ECOLOGY

Inbreeding and Metapopulations

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Probably the oldest observation about population genetics is that individuals produced by mating between close relatives are often less healthy than those produced by mating between more distant relatives. This inbreeding depression is so obvious that most human cultures prohibit marriage between close relatives, and animal breeders know to avoid inbreeding their animals. But it is only recently that the importance of inbreeding depression to natural animal populations has been realized (*1*, *2*). On page 485 of this issue, Ebert, Haag, and co-workers (*3*) show just how important inbreeding can be.

Ebert *et al.* studied natural populations of the water flea *Daphnia magna*, a small crustacean that lives in temporary rock pools. In a simple but clever experiment, these investigators took advantage of the fact that there are thousands of natural rock pools that potentially sustain *Daphnia* on the islands in the Baltic Sea. For 22 pools, they removed all *Daphnia* and then reintroduced 200 of them (the residents) with 200 from a different pool (the immigrants). There was enough genetic differentiation among pools to be able to distinguish genetically among the residents, immigrants, and hybrids between them. After one round of sexual reproduction, the fate of these three different genotypes was determined by their relative fitness in the following year. During most of the summer *Daphnia* reproduce asexually, which allowed the fitness differences between the genotypes to be magnified by many generations of selection on genetically identical clones.

What they found at the end of the summer was impressive. In all of the replicates in which the hybrid genotypes were found, the frequencies of the hybrids increased, usually substantially, with the average relative fitness of hybrids being 36 times that of nonhybrids. The fact that the different immigrant populations were genetically distinct rules out the possibility that the observed hybrid success was caused by immigrants carrying superior genes. Furthermore, the experiment was performed in parallel in the laboratory with the same genetic pairs of

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