"ordinary"—and a thicker detector of higher quantum efficiency, he expects that exposure time can be cut a hundredfold. In any case, the wide band-pass acceptance of the new grating-based method allows much shorter exposure times than crystal-based dark-field imaging would require with a spectrally broad x-ray source of comparable brightness.

Absorption of x rays decreases with increasing energy, and soft tissue is less absorbing than bone. Therefore conventional clinical imaging of soft tissue—mammography, for example—is done with relatively low-energy hard x rays of about 30 keV to insure adequate absorption. But absorption and its attendant ionization are precisely what subjects the patient to radiation risk. Because dark-field imaging does not depend on absorption, it could be done with less hazardous 100-keV x rays. "That shouldn't be difficult," says Pfeiffer. "But it will require the fabrication of diffraction gratings thick enough to absorb the more penetrating high-energy x rays."

Bertram Schwarzschild

References

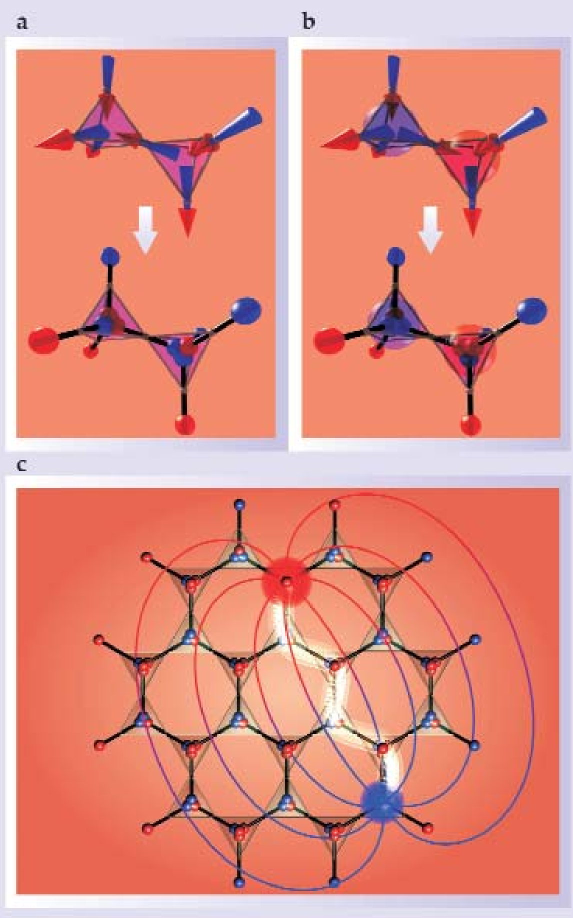
1. See, for example, T. J. Davis et al., *Nature* **373**, 595 (1995); L. E. Levine, G. G. Long, *J. Appl. Crystallogr.* **37**, 757 (2004); and M. Ando et al., *Nucl. Instrum. Methods Phys. Res. A* **548**, 1 (2005).
2. F. Pfeiffer et al., *Nat. Mater.* **7**, 143 (2008).
3. F. Pfeiffer et al., *Nat. Phys.* **2**, 258 (2006).

Elementary excitations in spin ice take the form of magnetic monopoles

A magnet has two poles—north and south. But in a frustrated magnetic state known as spin ice, the familiar magnetic dipole can split into two magnetic charges that independently diffuse around the crystal.

Ferromagnetism—the ability of materials such as iron to form permanent magnets—arises from the spontaneous alignment of atomic spins when atoms interact with each other. But some magnetic solids, especially ones that are geometrically frustrated, exhibit rich and complex effects of those interactions. The behavior of a solid depends not just on the positions of its atoms but also on their local properties—the electric, magnetic, or rotational degrees of freedom. So when the energetically preferred alignment of magnetic moments in a lattice is incompatible with the underlying crystal geometry, exotic phases can emerge (see the article by Roderich Moessner and Art Ramirez in PHYSICS TODAY, February 2006, page 24).

One of those phases, spin ice, is a strange magnetic state in a material whose ions reside on the vertices of the pyrochlore lattice, a network of corner-sharing tetrahedra. A strong crystal field produced by the local environment of the ion favors an arrangement in which spins point either into or out of the centers of each tetrahedron. But as the temperature falls, geometric frustration inhibits the formation of a simple, ordered spin configuration in which every bond connects an in–out pair.



Mapping dipoles to dumbbells. The magnetic moments in spin ice reside on the sites of the pyrochlore lattice, which consists of corner-sharing tetrahedra. The energy-minimizing ground states are described by the "ice rule": Two spins point out of each tetrahedron and two spins point in. **(a)** If the spin at each pyrochlore lattice site is stretched to span the centers of neighboring tetrahedra, with opposite magnetic charges at either end of a dumbbell, the ice rule is obeyed when the net charge of each tetrahedron is zero. **(b)** Inverting the shared spin in a pair of tetrahedra generates a monopole–antimonopole pair (the large red and blue balls). **(c)** As pictured in this slice of the pyrochlore lattice, thermal energy can prompt the oppositely charged monopoles to separate along a path (outlined in white) of adjacent tetrahedra. Once created at a finite temperature, the monopoles thus become independent, long-lived topological defects in the crystal. Magnetic field lines connect the two monopoles. (Adapted from ref. 1.)

To minimize the energy, the best compromise is one in which two spins point into and two point out of each tetrahedron. That simple organizing principle, called an ice rule by analogy to the way hydrogen atoms are positioned around a central oxygen atom in water ice, can be satisfied by an exponentially large number of energetically equivalent arrangements of spins. The huge set of degenerate ground states is responsible for a characteristic property of spin ice: Although the material is structurally ordered, it remains magnetically disordered—and thus retains a residual, zero-point entropy—even as its temperature approaches absolute zero.

Claudio Castelnovo (Oxford University), Roderich Moessner (Max Planck Institute for the Physics of Complex Systems, Dresden), and

Shivaji Sondhi (Princeton University) have discovered another remarkable property of spin ice: Its localized excitations above the ground state form a new and unexplored class of solid-state defects—magnetic monopoles that can split from their parent dipole and diffuse around the crystal as free charges.[1]

In crystals at low temperature, elementary excitations often behave like particles. Solitons, phonons, and magnons, for example, are all quasiparticles that carry quantized amounts of energy, momentum, or spin and emerge from the collective interactions of many atoms. What distinguishes spin ice is that it is the first example of a three-dimensional system that behaves as if its fundamental building block, the electron spin, breaks apart—much like the electric charge does in the two-dimensional fractional quantum Hall effect (see reference 2 and the article by Philip Anderson in PHYSICS TODAY, October 1997, page 42). Through the subtleties of many-body physics, the spin-ice system mimics the properties of a dilute gas of magnetic monopoles.

Splitting the dipole

Spin-ice compounds are among the most densely magnetic of all substances. The magnetic dipoles are closely packed, and their dominant interactions are long-range and strongly anisotropic due to the coupling of spin and position vector components in the dipolar spin Hamiltonian. To calculate with so complex a Hamiltonian, theorists in recent years have had to rely on numerical simulation. But the complexity raises the question, Why does the simple (and local) ice rule work so well?

Researchers have long suspected that the ice rule is not a purely local effect acting among nearest-neighbor ions but rather an emergent, many-body property of the long-range interactions.[3] Castelnovo, Moessner, and Sondhi discovered the unusual excitations in spin ice using a model that accounts for the empirical observation that ice-rule states are roughly equivalent to the ground states of dipolar interactions. In essence, the researchers reframe the Hamiltonian from one based on the sum of interacting dipoles to one based on the sum of local magnetic charges, which they identify as the natural degrees of freedom at low energies.

The effective change to the Hamiltonian is slight, it turns out, and akin to a coordinate transformation that vastly simplifies the calculation. The interaction energy of each magnetic dipole living on a pyrochlore lattice site is replaced by the energy of a pair of opposite magnetic charges, one in the center of each neighboring tetrahedron. To visualize the idea, imagine the spins stretched into dumbbells, as pictured in the figure on page 16. The crucial insight is that in the ground state the four magnetic charges (two positive, two negative) in each tetrahedron cancel each other out. Long-range dipole interactions are, on average, screened out, so that the magnetic field in the system vanishes when the configuration obeys the ice rule.

What about excited states? The most elementary excitation is the inversion of a single dipole to generate a local net di-

physics update

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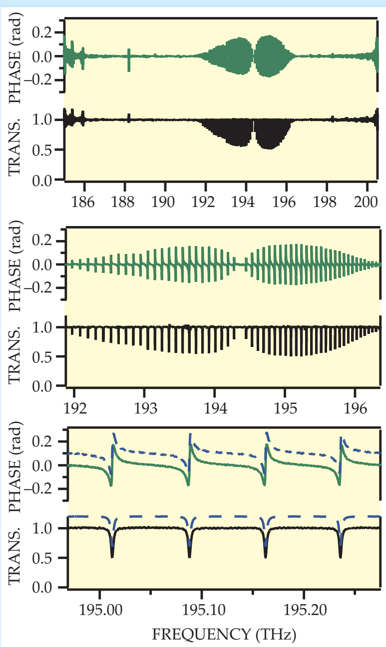
Broadband frequency-comb spectroscopy. An optical frequency comb is a collection of exceedingly sharp and precisely spaced radiation "teeth" in the frequency domain, generated by a train of light pulses from a mode-locked femtosecond laser. More than 10^5 such teeth, each one a narrowband oscillator, can be packed into a few-hundred-nanometer spectral range. The problem for spectroscopists, however, lies in separately detecting each individual comb tooth. Three physicists at NIST in Boulder, Colorado, have now done that. The trio sent the signal comb through a gas sample to be analyzed. A second, minutely different comb was used for reference, and the resulting "heterodyne beat" between the two generated a third comb in the RF range where each tooth could be easily resolved and mapped back to the original signal. In that way, the group measured the spectrum of hydrogen cyanide gas over a wavelength range of 125 nm. In just a few seconds, they obtained absorption and phase shift information for 155 000 individual frequency lines at a spacing of 100 MHz; some of those lines are shown at left. The bottom panel also depicts the good agreement with calculated phase and previously measured absorption, both shown as offset broken lines. A frequency accuracy of 1 Hz is possible, say the researchers, who think their work might change the way people perform spectroscopy. For example, the rapid acquisition of high-resolution broadband spectra could be useful in studies of dynamic chemical or biological systems. (I. Coddington, W. C. Swann, N. R. Newbury, *Phys. Rev. Lett.* **100**, 013902, 2008.) —PFS



Putting the squeeze on ferroelectrics. Piezoelectric materials display cause and effect between mechanical deformation and electric field; applying either generates the other. Ferroelectric materials have a spontaneous, measurable electric dipole moment even in the absence of an electric field; an applied field can greatly increase that polarization. Combining the two properties is the technological basis of many actuators and other devices. The most useful such devices have their largest electromechanical response in a narrow region of their compositional phase diagram, a region dubbed the morphotropic phase boundary (MPB). To meet the appropriate criteria, modern devices are generally made from complex, engineered materials. Enter some physicists from the Carnegie Institution of Washington, who found an MPB in a pure compound—lead titanate—under pressure. The researchers obtained both synchrotron x-ray diffraction and Raman spectroscopy data for $PbTiO_3$ under low-temperature, high-pressure conditions and discovered that even a pure material can show very large piezoelectric effects—in fact, the largest yet known. The scientists suggest that mechanical pressure could be replaced with chemical pressure by substituting a smaller atom with similar pole moment. The inversion breaks the ice rule in neighboring tetrahedra and creates two magnetic charges $\pm q_m$, a nearest-neighbor monopole–antimonopole pair represented by the large colored balls in the figure; one monopole represents a state in which three spins point out and one in, while the other represents a state in which one spin points out and three in. The monopoles can be separated from each other without further violations to charge neutrality by flipping a chain of adjacent dumbbells. Indeed, one can envision monopoles in spin ice as magnetic analogues of electrically charged defects H_3O^+ and OH^- in water ice.

Deconfined monopoles migrate independently around the bulk crystal. A pair separated by a distance r experiences a Coulombic potential $-\mu_0 q_m^2/(4\pi r)$, where μ_0 is the vacuum permeability. Because they are embedded in a crystal with a fluctuating magnetization **M**, the monopoles can act as sources and sinks of the magnetic field **H** while still preserving a zero divergence in the magnetic flux density **B**, in accord with Maxwell's equations.

Finding monopoles

At least conceptually, detecting the presence of a monopole is straightforward. The magnetic flux measured in a superconducting quantum interference device wrapped around a wire of spin ice should change as a monopole drifts down the wire and through the SQUID. Practically, the experiment is tough. The charge on a spin-ice monopole is tiny, roughly 1/8000 the charge of an elementary Dirac monopole, so the measured change in a SQUID would be 1/8000 the flux quantum $h/2e$. Moreover, the monopoles must be dilute enough that just one or two of them diffuse through the SQUID at any one time. The temperature required to guarantee that is so low that other issues become more worrisome—in particular, the dynamics become very slow.

Castelnovo and colleagues take a different approach to building confidence in their theory. By applying a magnetic field along a crystallographic direction in spin ice, they argue, one can essentially tune the density of monopoles. Varying the magnetic field at different temperatures maps out the system's phase diagram.

Five years ago, researchers observed[4] a line of first-order phase transitions in the spin ice dysprosium titanate below a critical temperature of about 0.36 K in an applied magnetic field around 0.9 T. How to interpret the transition has remained mysterious until now, says Moessner. By accurately reproducing the phase diagram, the new spin-ice model accounts for the transition as the condensation of a dilute gas of monopoles into a dense liquid.

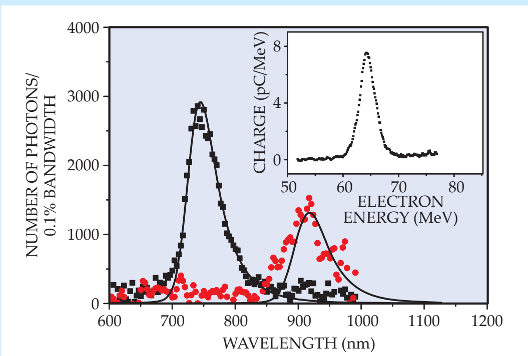
Mark Wilson

References

1. C. Castelnovo, R. Moessner, S. L. Sondhi, *Nature* **451**, 42 (2008).
2. R. B. Laughlin, *Rev. Mod. Phys.* **71**, 863 (1999).
3. For a review of spin ice, see S. T. Bramwell, M. J. P. Gingras, *Science* **294**, 1495 (2001).
4. T. Sakakibara, T. Tayama, Z. Hiroi, K. Matsuhira, S. Takagi, *Phys. Rev. Lett.* **90**, 207205 (2003).

polarizability for Pb. Designing simple electromechanical materials using chemical substitution could greatly decrease costs and increase utility of ultrasonic and other actuators. (M. Ahart et al., *Nature* **451**, 545, 2008.) —SGB

Synchrotron radiation from a plasma wakefield accelerator. A mainstay of the materials-science and bioscience research communities, the synchrotron light source provides a powerful, though large and expensive, probe of substances from the exotic to the mundane. To shrink those synchrotrons from



today's giant user facilities to something that can fit in a basement room is the goal of a multinational team led by Dino Jaroszynski (University of Strathclyde, Glasgow, UK). In a first step, the physicists coupled a high-intensity femtosecond laser, a plasma, and an undulator—a series of magnets through which electrons wiggle—to generate bursts of narrowband visible light. The intense field of a laser pulse produces waves in the plasma and rapidly accelerates electrons in a very short distance. Those high-energy electrons then navigate the undulator, radiating as they go. In the figure, the black dots show the light from the electron pulse depicted in the inset, while the red dots are from a different shot. In these early experiments, only about 1 in 10 laser pulses produced monoenergetic electron bunches, but the researchers think improvements can greatly increase the reproducibility and stability of the shots. Because laser-wakefield synchrotrons would be compact, inexpensive, and able to radiate from x rays down to microwaves, Jaroszynski says they could enable a wide range of applications in research, medicine, and industry. (H.-P. Schlenvoigt et al., *Nat. Phys.* **4**, 130, 2008.) —SGB

Saxophonists tune vocal tracts. Saxophone great John Coltrane had a sound that is instantly recognizable to an experienced listener. His distinctive style arose in part from resonances in the frequency-dependent acoustic impedance (proportional to sound pressure) of his throat and mouth. Of course, the saxophone, which typically has a sharp impedance peak near the frequency of the note being played, also makes an important contribution. For some 25 years, acousticians and musicians alike have debated the vocal tract's influence on an instrument's sound. Now, Jer Ming Chen and colleagues at the University of New South Wales in Sydney, Australia, have addressed the question quantitatively—at least for the tenor saxophone, whose innards are big enough to house the researchers' measuring equipment. The Sydney group determined that in the tenor's lower range, resonances in the saxophone's impedance are much stronger than those in a musician's vocal tract. So the tract resonance need not be, and typically is not, tuned to the note sounded. But the strength of the instrument's resonances decreases as the frequency of the note increases. To play a note in the so-called altissimo range, which comprises notes higher than the instrument was designed to play, the vocal-tract resonance needs to be significantly stronger than the instrument's. And to tune the tract resonance to those super-high frequencies is a challenge—one met by the professional saxophonists but not by the amateurs in the study. (J. M. Chen, J. Smith, J. Wolfe, *Science* **319**, 776, 2008.) —SKB ■