Physics News in 2003

A Supplement to APS News

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INTRODUCTION

Physics News in 2003, a summary of physics highlights for the past year, was compiled from items appearing in AIP's weekly newsletter *Physics News Update*. Many of the entries appearing here were also published in *Physics Today* magazine, where they were edited further by Stephen Benka. Readers should keep in mind that because of the way *Physics News Update* itself is prepared (short items aimed primarily, but not exclusively, at science journalists) and because of limited space in this supplement, some physics fields and certain past contributions to particular research areas might be under-represented in this compendium.

Furthermore, these items mostly appear as they did during the year, and the events reported therein might have been overtaken by newer results and newer publications which might not be reflected in the reporting. Readers can get a much wider view of the year's worth of physics by going to the *Physics News Update* website at http://www.aip.org/physnews/update or APS's *Physical Review Focus* website at http://focus.aps.org/.

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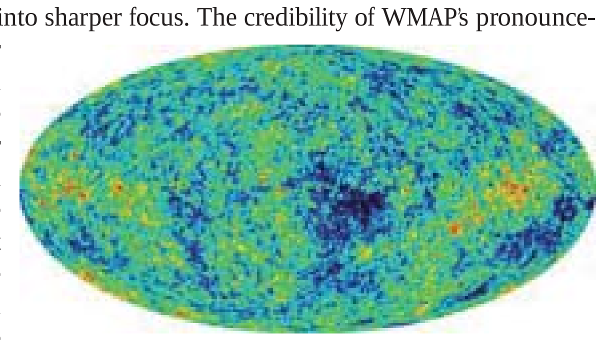
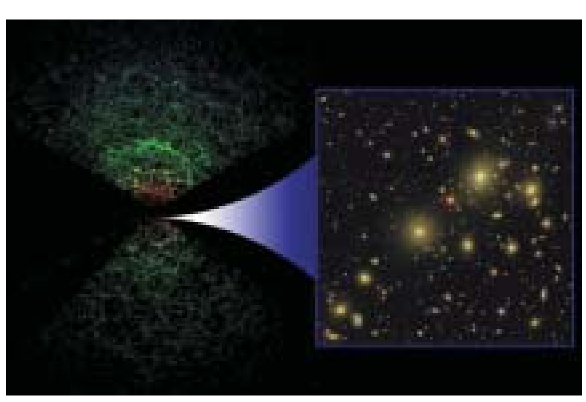
ASTROPHYSICS

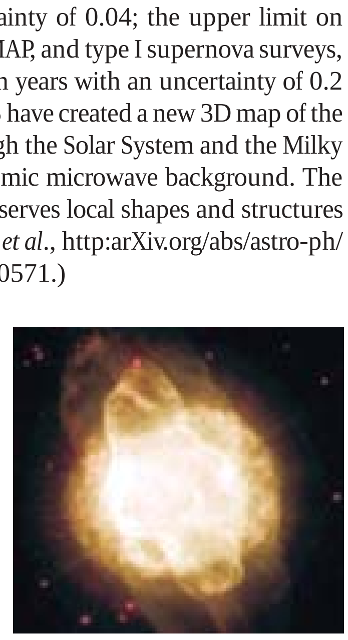
A PINPOINT PRECISION MAP OF THE COSMIC MICROWAVE BACKGROUND, reported by scientists associated with the orbiting Wilkinson Microwave Anisotropy Probe (WMAP), brings the early universe into sharper focus. The credibility of WMAP's pronouncement rests on three things: its angular resolution is some 40 times better than that of its microwave predecessor, the Cosmic Background Explorer (COBE); it comprehensively surveyed the entire sky for a whole year (3 more years of data is yet to come); and it measures the polarization of the microwave radiation; the orientation of the radiation arises partly from the last scattering of light at the time of "recombination," when stable atoms formed for the first time, and partly from the time when ultraviolet radiation strewn by the first generation of stars ionized once again a lot of atoms in space. The image shows a microwave picture of the sky as recorded by WMAP. Here are a few of the salient numbers coming out of the WMAP analysis: the time of recombination was 380,000 years after the big bang; the era of the first stars was about 200 million years after the big bang (surprisingly early); the age of the universe is 13.7 billion years; the accounting of matter in the universe is as follows: atomic matter makes up about 4%, dark matter about 23%, and dark energy 73%. (13 papers released in February 2003: astro-ph/0302207-09, 13-15, 17, 18, 20, 22-25)



OUR KNOWLEDGE OF THE UNIVERSE HAS BEEN SHARPENED thanks to new data from the Sloan Digital Sky Survey (SDSS). Using observations of more than 200,000 galaxies, the SDSS team measured, with small and well-controlled systematic errors, the three-dimensional galaxy power spectrum of the universe. Those data alone provide strong new constraints—for example, on the matter spectrum—and independent confirmation of the basic theoretical framework of modern cosmology. The image, courtesy of the SDSS, shows a 2D image of galaxies on the right, and on the left, displays how the galaxies are fitted into a 2 billion light-year-deep 3D image. When combined with data from the Wilkinson Microwave Anisotropy Probe (WMAP), the new Sloan observations help tamp down uncertainties in several pivotal cosmological numbers. The new best value for the Hubble constant is 0.70 with an uncertainty of about 0.04; the matter density is 0.30, also with an uncertainty of 0.04; the upper limit on neutrino mass is now 0.6 eV. Combining data from SDSS, WMAP, and type I supernova surveys, the age of the universe has now been found to be 13.5 billion years with an uncertainty of 0.2 billion years. In a separate project, astronomers from the SDSS have created a new 3D map of the universe that shows features ranging from Earth's core, through the Solar System and the Milky Way galaxy, past the galaxies of the SDSS, and out to the cosmic microwave background. The cosmic cartographers say that the conformal map, which preserves local shapes and structures at every stage, is suitable as an educational tool. (M. Tegmark *et al*., http:arXiv.org/abs/astro-ph/0310723; J.R. Gott III *et al*., http://arXiv.org/abs/astro-ph/0310571.)



A VERY LONG LIVED ATOMIC STATE has been measured in an astrophysical nebula. Most excited atomic states last much less than a second. The lifetimes of longer-lived states are difficult to measure because collisions between atoms cause deexcitations before the atoms can decay radiatively. With a vacuum far better than any on Earth, outer space is the laboratory of choice for such atomic measurements. That's why Tomas Brage of Lund University (Lund, Sweden), Philip Judge of the High Altitude Observatory (Boulder, Colorado), and Charles Proffitt of Computer Sciences Corp (Baltimore, Maryland) turned their gaze on the planetary nebula NGC3918. Amid that wreckage of a dying star, there is enough energy to excite atoms but a low enough density (a few thousand atoms per cubic centimeter) that collisions are not a problem. Using the Hubble Space Telescope, the scientists looked at the emissions from triply ionized nitrogen atoms and found a lifetime of 2500 seconds for one particular hyperfine-induced transition in which a nuclear spin flip induces an electronic transition. The measurement provides important confirmation of earlier calculations, and thus lends support to theoretical studies of both atoms and large-scale, low-density astrophysical sources. (T. Brage, P. G. Judge, C. R. Proffitt, *Phys. Rev. Let*. **89**, 281101, 2002.)



CAN THE SPEED OF GRAVITY be measured directly through the observation of gravitational lensing effects? Sergei Kopeikin (University of Missouri) and Ed Fomalont (National Radio Astronomy Observatory) used the exquisitely sensitive Very Long Baseline Array of radio telescopes to monitor Jupiter's gravitational deflection of light from a distant quasar that was nearly aligned with the massive planet on 8 September 2002. At the January 2003 meeting of the American Astronomical Society in Seattle, the researchers reported that the apparent position of the quasar traced a small loop over the course of several days. Moreover, they argued, the precise measurement of the loop's shape allows one to determine the speed of gravity. Their result, that the speed of gravity equals 1.06 ± 0.21 times the speed of light, is consistent with Einstein's theory of relativity. The experiment is widely regarded as a tour de force. But Washington University's Clifford Will, and other scientists, argue that the reported data are in no way related to the speed of gravity. (E. B. Fomalont, S. M. Kopeikin, http://arxiv.org/abs/astro-ph/0302294; C. M. Will, http://arxiv.org/abs/astro-ph/0301145.)

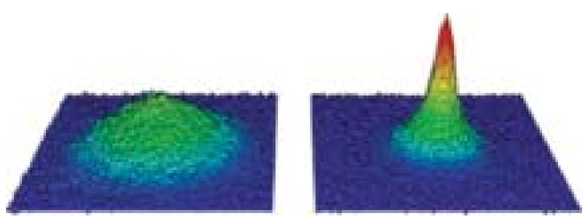
FIRST SCIENTIFIC RESULTS FROM LIGO (the Laser Interferometer Gravitational-Wave Observatory). Essentially a giant strain gauge to measure the local distortion in spacetime of a passing gravitational wave, LIGO has detectors in Hanford, Washington, and Livingston, Louisiana. (For more on LIGO's operation, see *Physics Today*, October 1999, page 44.) The ripples in spacetime radiated, for example, by the collapsing inspiral of two neutron stars are predicted to produce a strain in LIGO of perhaps one part in 10^{20}, which would change the distance between mirrors some 4 km apart by about 10^{-18} meters, a displacement 1000 times smaller than a proton. At the April 2003 APS meeting, the LIGO team reported its first official results from the initial science run, conducted over 17 days in the late summer of 2002. Gary Sanders (Caltech) and Erik Katsavounidis (MIT) reported that, as expected, no gravitational-wave events were seen, but new upper limits were set on three of the four prime source categories. For coalescing binaries, no more than 164 events per year are expected from the Milky Way or an equivalent galaxy. The limit for both known and unknown burst sources, at a strain of 10^{-17}, is 1.4 events per day. Using one pulsar as a test case, LIGO has demonstrated sensitivity to pulsar sources at a strain amplitude of 10^{-22}, within a factor of 100 of that expected from the Crab pulsar. Finally, LIGO's limit on stochastic waves that could have arisen in the early universe—expressed as their contribution to the energy density needed to close the universe—has Omega as less than 72.4, a bit higher than the current best limit of 60. All of these limits are expected to improve dramatically after data from the recently concluded second science run, with its tenfold increase in sensitivity, are analyzed.

THE BIG RIP. A new cosmic doomsday scenario takes the present acceleration of the expansion of the universe to extremes. In the wake of observations of distant supernovae (see the article by Saul Perlmutter in *Physics Today*, April 2003, page 53), cosmologists generally apportion 70% of the universe's energy inventory to an enigmatic dark energy. The new relevant parameter, which must be less than -1/3, is w, the ratio of the dark energy's average pressure to its energy density. The widely known cosmological-constant and quintessence models explore values of w between -1/3 and -1. But what if w is less than -1? In that "phantom energy" case, Dartmouth College physicist Robert Caldwell with Marc Kamionkowski and Nevin Weinberg of Caltech have now determined that eventually all bound objects—galaxies, stars, planets, atoms, nuclei, and nucleons—will be torn apart. Caldwell suggests that deciding between their model and the others might be possible in coming years with much better measurements of the microwave background, supernovae, and galaxies. (R. R. Caldwell *et al.*, *Phys. Rev. Lett*. **91**, 071301, 2003.)

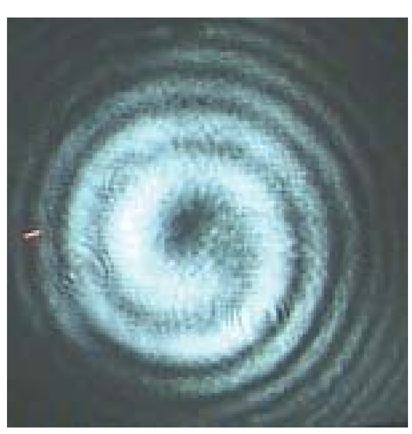
DIRECT IMAGING OF EXTRASOLAR PLANETS (sometimes called exoplanets) might be easier than astronomers thought, according to a new study. Evidence for the existence of planets around nearby stars is mostly indirect—tiny Doppler shifts in a star's spectra or a minute dimming of a star's emission. Direct imaging of an exoplanet is problematic because of the overwhelming brightness of the nearby star. One proposed way of getting around the glare is to use nulling interferometry, which combines the light waves from two or more telescopes so as to minimize the total signal. With this technique, a dim object, like a planet, might suddenly emerge from what had been irrepressible glare. Now, William Danchi (NASA's Goddard Space Flight Center in Greenbelt, Maryland) and his colleagues have extensively studied the capability of nulling infrared interferometry. They found that, for two reasons, the instrument's angular resolution can be an order of magnitude better than conventionally assumed. First, the interferometer's response decreases quadratically inside the null while the number of signal photons increases exponentially as the planet gets closer to the star. An exponential always wins, so the planet's signal remains strong. Second, the team used the ratio of two IR wavelengths in a way that rendered the observation insensitive to fluctuations in the optical pathlength of the system. The astronomers simulated observations of all known exoplanets and found that several could be directly imaged with even a modest instrument—two 0.5-m telescopes set 12.5 m apart—and spectra could be obtained of their atmospheres. (W. C. Danchi *et al.*, *Astrophys. J. Lett*. **597**, L57, 2003.)

ATOMIC, MOLECULAR, AND OPTICAL PHYSICS

BEC MADE FROM FERMION MOLECULES. The study of quantum gases, gases that display spectacular quantum effects, has come under sharp scrutiny over the past decade, partly because they offer the chance to study a model quantum system in which the interaction among atoms can possibly be tuned at will by the researcher. Chilled gases are not all alike. Cold clouds of boson atoms can fall into a single quantum state known as a Bose Einstein condensate (BEC). BEC was first observed in 1995 for the case of bosonic rubidium atoms (at NIST/Colorado), lithium atoms (Rice Univ), and sodium atoms (MIT). Meanwhile, fermion atoms must avoid consorting with each other in any unified quantum state (a behavior enforced by the Pauli exclusion principle, which also dictates how electrons in atoms group into discrete shells). This means condensation is out of the question. Fermi atoms can, however, show off their quantum nature by piling up into all possible quantum energy levels allowed by the ambient temperature inside an atom trap in a degenerate fermi gas. This feat was achieved in 1999 by another NIST group. Now, in the latest chapter in the saga of quantum gases, several groups have succeeded in producing a BEC of molecules made from pairs of fermion atoms. Note that the atoms are fermions but considered as pairs they are bosons and therefore able to condense in Bose Einstein fashion. Rudolf Grimm and his colleagues at the University of Innsbruck (publishing online in *Science* 14 November 2003, abstract 1093280) used lithium atoms, while Deborah Jin and her colleagues at NIST (publishing online in *Nature*, preprint on www.arxiv.org) used potassium atoms. The false-color image shows the formation of the potassium BEC at NIST. Wolfgang Ketterle (MIT) has also made a long-lived Fermi-molecular BEC (Zwierlein *et al.*, *Phys. Rev. Lett.*, **90**, 25040, 2003).



A NEW OPTICAL GEOMETRIC PHASE has been measured for the first time, by a group of physicists at Colgate University. The new geometrical phase is associated with light beams carrying orbital angular momentum. This development can be considered yet another step toward understanding and exploiting the weirdness of quantum reality for performing novel feats of computation.



What does it mean for light to have "orbital" angular momentum? What is it that orbits?

To ponder this issue, picture the electric field values for a vertical planar slice of the light beam. For vertically polarized light, the electric field at all the points on the slice is vertically oriented. Look at the same slice at a later time and the fields are still vertically oriented. For circularly polarized light, the fields in the slice will, at a certain moment, also be oriented in the same way. A moment later, however, the electric field will have precessed a bit (from the one o'clock position, say, to the three o'clock position; another way of saying this is that the phase of the electric field will have advanced a bit) but the orientation of the field at each point on the vertical slice will be the same. With the use of special gratings one can produce an entirely different mode of light, one in which the electric field phase coils around the beam axis, and the light is said to possess an orbital angular momentum, or OAM.

The picture, produced at Colgate University, shows an interference pattern that manifests the orbital angular momentum of the light. This "coiled light" might be exploitable for future quantum computing. For instance, recently a group at the University of Vienna used OAM in light to create a three dimensional entangled state, or "qutrit" (Vaziri *et al.*, *Physical Review Letters*, 9 Dec 2002). When a light pulse is made to follow a closed loop path in real space, the phase of the returning beam might be slightly off from the phase of light starting off at that point. This disparity (which can result in an interference effect) can be modified by changing the path length. It can also be modified by changing the path geometry.

In addition, the space does not need to be real space. When the "mode" (set of standing waves in the beam) is changed, it can also produce a phase when changing the geometry of the path in "mode space," and it is this that the Colgate physicists have measured.

The change in phase that a quantum system undergoes in going around a closed path in a space of states or parameters is called a "geometrical phase," and can be measured when the light emerges from the path to form a spiral shaped interference pattern at an external detector (Galvez *et al.*, *Phys. Rev. Lett.*, **90**, 203901, 2003)

REFRACTION AT THE ATOMIC LEVEL. In general, the speed of light in a dense medium is determined by the medium's refractive index, which can vary significantly from that in vacuum. A highly dispersive medium—one in which the index of refraction varies rapidly with frequency—can allow greatly slowed or even speeded up group velocities for light. Now, researchers from the University of Tokyo (Japan) and NIST (Maryland) have altered a light pulse's speed in a microcavity with a medium— less than 10 rubidium atoms—whose density scarcely differs from vacuum. The secret to the effect is a long dwell time. The 70-mm-long cavity was so reflective (its "finesse" was high) that the pulse reflected many times before leaking out. Thus the light interacted repeatedly with the handful of atoms, which makes the macroscopic concept of refractive index meaningful. The pulses used in the experiment were themselves quite ephemeral, amounting to only an average of four-tenths of a photon in the cavity at any one time. The researchers plan to look for single-atom effects in the cavity. (Y. Shimizu *et al.*, *Phys. Rev. Lett*. **89**, 233001, 2002.)

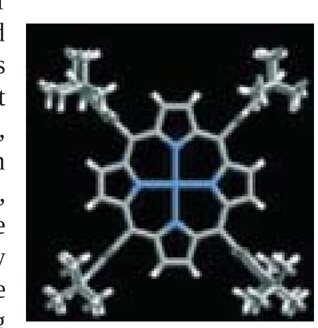
THE PHOTONIC DE BROGLIE WAVELENGTH of entangled photon pairs has been directly measured. In the early days of quantum mechanics, Louis de Broglie argued, and it was soon demonstrated, that if waves could act like particles (as in the photoelectric effect), then particles could also act like waves. By now, the wave nature of molecules as large as buckyballs (carbon-60) has been demonstrated. For composite objects, the de Broglie wavelength depends fundamentally on the object's internal structure. For an ensemble of photons taken collectively, the de Broglie wavelength is lambda/N, the wavelength of an individual photon divided by the number of photons. This was verified in 1999 for a two-photon wavepacket in a double-slit experiment. Physicists at Osaka University in Japan have now demonstrated that the relation still holds for spatially separated, entangled photons. Through parametric down-conversion, they transformed a photon of wavelength lambda into an entangled pair of photons (a biphoton) of wavelength 2 times lambda. Those photons were then sent along different paths through an interferometer. When the single-photon interference for either member of the pair was measured, it showed a wavelength of 2 lambda.

However, the measurement that preserved the entanglement yielded lambda. The physicists also showed that the coherence length of the biphoton was much longer than for the 2 lambda single-photon case. They say that the concept remains valid for more than two entangled photons. Eventually, it may be possible to generate entangled photons from nonentangled photons of the same wavelength, a process called hyperparametric scattering. (K. Edamatsu, R. Shimizu, T. Itoh, *Phys. Rev. Lett*. **89**, 213601, 2002.)

X-RAY INTERFEROMETRY has been achieved in a cavity. Owing to their high energies, x-rays are notoriously difficult to reflect at high angles to a surface. Indeed, x-ray telescopes in orbit use grazing-incidence mirrors to gradually focus x-rays onto a detector. Recently, however, physicists at the University of Hamburg, Germany, succeeded in reflecting x-rays directly back from special sapphire crystal mirrors. The price for achieving normal-incidence reflectivity is that it operates only over a few-meV spectral range near a fixed energy determined by Bragg's law. The group used the mirrors to build a prototype Fabry-Pérot interferometer (resonator) for hard x-rays. In their instrument's 50-mm cavity, the physicists observed as many as 60 reflections, and measured 0.76-meV-wide resonances for 14.3 keV x-rays. The interference shows up as a modulation, in both time and wavelength, of the radiation that exits the cavity. The work could lead to high-resolution x-ray spectral filters, phase imaging with enhanced sensitivity, x-ray clocks, and a new way of calibrating length measurements at the atomic scale. The addition of a metallic film to the sapphire mirrors could also lead to new combined optical-x-ray devices. (Yu. V. Shvyd'ko *et al.*, *Phys. Rev. Lett*. **90**, 013904, 2003.)

TUNING OPTICAL FIBERS WITH MICROFLUIDICS. Optical fibers are a fundamental part of optical sensing, optical telecommunications, and many medical applications. One way to make the fibers even more efficient and versatile is to hand over some of the switching, tuning, and reconfiguring chores to the fibers themselves, rather than to rely on separate devices. Researchers at OFS Laboratories in Murray Hill, New Jersey, have now developed a tunable optical grating in a microstructured optical fiber. Their fiber has a hexagonal array of tiny air holes running its length, surrounding the 8-mm core where the light actually propagates. They created a tapered region, about 7 cm long, in the fiber so that the light field could expand beyond the core and interact with the air holes. With a vacuum applied at one end of the fiber, they alternately drew fluid plugs and air into the microchannels in the tapered region. The resulting periodic structure of fluid plugs was, in effect, a photonic crystal that caused resonant coupling of modes and wavelength-dependent attenuation. (C. Kerbage, B. J. Eggleton, *Appl. Phys. Lett*. **82**, 1338, 2003.)

LESS THAN 100 ZEPTOJOULES (100×10^{-21} joules, or 0.6 eV) to operate a molecular switch. That is some 10^{-4} of the energy needed by transistor switches in current high-speed computers. The porphyrin-based molecule Cu-TBPP was in the "on" position when one of its four legs was perpendicular to the copper surface on which it sat, and "off" when the leg was parallel. In a recent experiment, scientists from the University of Basel and IBM Zurich in Switzerland, and from the CEMES-CNRS lab in Toulouse, France, used an atomic force microscope tip not only to rotate the leg but also to measure the required force, from which they determined the energy. The authors suggest that a machine made from 10^{12} such interconnected nanodevices, operating at 1 GHz, would consume less than 100 W of power. (Ch. Loppacher *et al.*, *Phys. Rev. Lett*. **90**, 066107, 2003.)



OPTICAL PERISTALSIS. Part of the digestion process consists of peristalsis—the wave-like movement of powerful esophageal muscles urging food particles along the alimentary tract. Now, a similar sort of particle transport has been carried out at the nanoscopic level, using a holographic optical trapping (HOT) technique (which can confine atoms in a geometrical pattern). David Grier and Brian Koss at the University of Chicago use computer-designed holograms to project up to several hundred optical traps into a volume of about 3×10^5 μm^3. Each trap is a symmetric potential well that can hold a small amount of matter. By repeatedly changing to different holograms whose traps are displaced but overlapping with the previous ones, the matter can be shuttled deterministically, like a bucket brigade, along preordained paths of potential wells. Parallelism is one of the technique's strengths. When subjected to a sequence of hologram patterns with ever-increasing diameters, the spheres were transported radially outward, evacuating the central region. Reversing the sequence concentrates the spheres in the middle. Grier says that their HOT technique can create arbitrary configurations of optical traps in three dimensions and move all the traps independently under computer control. Optical peristalsis is a special case. (B. A. Koss, D. G. Grier, *Appl. Phys. Lett*. **82**, 3985, 2003.)

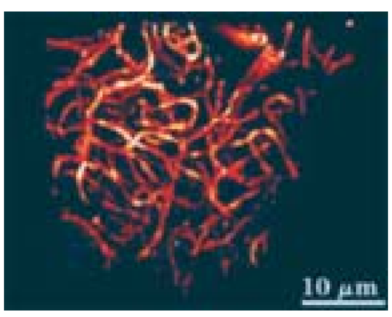
GIANT HELIUM MOLECULES have been created by researchers at the École Normale Supérieure in Paris. With atomic separations ranging from 8 to 60 nanometers, the diatomic molecules are comparable to the size of small viruses. Normally, He is chemically inert. To create the new giant molecular states, the researchers first cooled a gas of He atoms to 10 μK. Each atom was in a long-lived metastable state and carried nearly 20 eV of internal energy, more than 10^{10} times its average energy of motion. The physicists then used a laser to pair up He atoms through photoassociation, a process in which light-induced dipoles cause two atoms to bind to each other. To detect the molecules, the researchers recorded a temperature rise in the cloud; that increase resulted from the successful absorption of the laser light. In a typical experiment, 1% of the atoms absorb the light and form about 10^5 molecules. The atoms in each molecule are so far apart that they resist destructive auto-ionization effects in which an electron jumps from one atom to the other. To get theory to agree with the measured data, the researchers had to account for the finite speed of light through a retardation effect. The molecules lasted for a surprisingly long 50 nanoseconds. (J. Léonard *et al.*, *Phys. Rev. Lett.* **91**, 073203, 2003.)

A SPINLESS BOSE-EINSTEIN CONDENSATE, insensitive to external magnetic fields, has been created. Researchers at Kyoto University made their BEC with ytterbium-174, a rare-earth element with two valence electrons. The physicists used light beams to trap approximately 1 million Yb atoms in the singlet state, in which the valence electrons' spins point in opposite directions. The hotter atoms evaporated, leaving a gas cloud of about 5000 atoms that formed a magnetically unresponsive BEC at temperatures below 790 nK. The spinless BEC may be useful for precise atomic deposition and atom interferometry. Also, the heavy mass of Yb makes it desirable for studying certain fundamental physics effects, such as atomic parity violation and time symmetry violation. Moreover, the many stable isotopes of Yb (five are bosons, two are fermions) raise the possibility of creating a BEC and a Fermi degenerate gas in the same cloud. (Y. Takasu *et al.*, *Phys. Rev. Lett.* **91**, 040404, 2003.)

BIOLOGICAL

ALL-OPTICAL HISTOLOGY WITH FEMTOSECOND LASERS. To study the microscopic anatomy of tissue, histologists typically stain it, freeze it, slice it thinly, and sequentially look at the individual slices to get an overall picture. Now, a multidisciplinary and multi-institutional collaboration, led by neurophysicist David Kleinfeld (University of California, San Diego), has developed an automated, all-optical technique for cutting and imaging brain tissue.

As described by Jeffrey Squier (Colorado School of Mines) at the June 2003 CLEO/QELS meeting in Baltimore, Maryland, the researchers first stained or otherwise labeled a tissue specimen and then imaged the desired structures in 1-µm steps to a depth of about 150 µm, using nJ pulses of their laser. Next, with µJ pulses, they ablated the previously imaged tissue layer. The newly exposed layer was then stained (if necessary), the laser intensity was reduced to take another set of images, and the process continued until no tissue remained. Stacking up the successive images results in a diffraction-limited three-dimensional picture, such as that of the vasculature of mouse brain tissue shown here.



The laser ablation left a surface that was smooth to within 1-µm and preserved protein viability. Because the femtosecond technique completely destroys its tissue samples, it may be inappropriate for certain clinical applications like tumor biopsies, in which physicians wish to preserve the tissue for future reference. However, the automated technique may be well suited for many other applications in the burgeoning field of molecular medicine. (P. S. Tsai *et al.*, *Neuron* **39**, 27, 2003.)

THE ACTIVITY OF A SINGLE-ION CHANNEL PROTEIN has been detected with a new method. Ion channels act like pores with doors that allow ions to flow in and out of cells. That ionic current is how cells exchange information in various neural, cardiovascular, intestinal, and reproductive processes. The standard patch-clamp method for studying ion channels uses the tip of an electrolyte-filled micropipette that is connected to an amplifier. Now, scientists from the University of Munich, Germany, have replaced the pipette with micron-sized holes drilled into a glass chip. They use gentle suction to position and seal an individual cell onto a hole so that an ion-channel protein in the cell's membrane protrudes out the bottom.

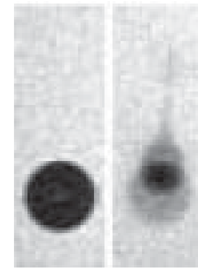
The researchers believe that this flat architecture will facilitate an automated bionanotechnological approach to ion-channel research. They add that the planar geometry also enables the combination of scanning-probe techniques or high-resolution fluorescence microscopy with simultaneous electrical recording. (N. Fertig *et al.*, *Appl. Phys. Lett.* **81**, 4865, 2002.)

SYNCHRONIZATION TOMOGRAPHY. A new brain imaging method pioneered by a German research group from several institutions can now produce images that localize the areas of the brain involved when test subjects perform physical activities, and can show how portions of the brain interact with each other. The technique, dubbed synchronization tomography, involves mapping the fluctuating magnetic fields produced by tiny electrical currents in the brain, and determining which brain regions are synchronized with an activity—such as a test subject's tapping finger. The researchers asked test subjects to tap their finger in time to a rhythmic tone, and to continue tapping at the same rate after the tone was switched off.

Meanwhile, their brain activity was mapped with a magnetoencephalography (MEG) machine. The maps showed that the same regions of the brain areas are active both as people tapped to a beat and as they paced the tapping themselves, but that the synchronization between the different brain areas changes dramatically. Other brain imaging methods, including functional magnetic resonance imaging (fMRI) and positron emission tomography (PET), can also provide insight into which regions of the brain are involved during various activities, but they take too long to acquire images to disclose how the brain regions interact with each other, and therefore overlook important details of brain function which are clearly revealed with synchronization tomography. In addition, a related synchronization technique may help in the study of rapidly changing signals in the heart detected with magnetocardiography systems. (P. A. Tass *et al.*, *Physical Review Letters*, **90**, 088101, 2003.)

SINGLE-MOLECULE, SINGLE-BASE-RESOLUTION DNA SEQUENCING has been demonstrated. Decoding single-molecule DNA strands is intrinsically difficult because of the high linear data-storage density: The base molecules are only about 3.4 Å apart. Now, a group at Caltech has used a DNA polymerase enzyme to add complementary base units, one at a time, to a single strand of DNA. The base molecules being added were fluorescently labeled beforehand, so the newest member of the DNA sequence at each stage could be observed as it fluoresced. The scientists minimized background noise through careful use of two laser pulses: one to produce pinpoint fluorescence and the other to null or "bleach" the fluorescence to prepare for the next base incorporation. Thus far, sequences of up to six bases have been read. Stephen Quake believes that, within about two years, his group's process should be a factor of ten faster than standard gel-electrophoresis techniques currently used to sequence DNA molecules, and several orders of magnitude cheaper. (I. Braslavsky *et al.*, *Proc. Natl. Acad. Sci. USA* **100**, 3960, 2003.)

USING BUBBLES TO DELIVER DRUGS IS A STEP OR TWO CLOSER TO REALITY. Claus-Dieter Ohl and Roy Ikink (University of Twente, the Netherlands) found that tiny bubbles (7-55 µm across) floating in water develop needlelike tips when exposed to acoustic shock waves. The effect was seen with pressure amplitudes of 11-21 MPa, much smaller than needed, for example, to break up kidney stones. The tips formed in the direction of the propagating shock, when the liquid surrounding each bubble was accelerated through the bubble's center and pierced the opposing bubble wall, much like the jet from a syringe (as depicted in the photograph). The researchers suggest that, if the tip can actually penetrate a cell's membrane, then drug-coated bubbles could be used for *in vivo* local drug delivery. Separately, Phillippe Marmottant and Sascha Hilgenfeldt (also at Twente) have experimented with bubbles attached to a substrate. They showed that very gentle bubble oscillations—in an acoustic field of only 0.01 MPa—can set up a flow field that attracts a nearby cell, ruptures its membrane, and then repels the cell. The "sonoporation" technique could prove useful not only for exchanging a cell's interior and exterior fluids in drug or DNA delivery, but also in other cell manipulation or microfluidic applications. (C. D. Ohl, R. Ikink, *Phys. Rev. Lett.* **90**, 214502, 2003; P. Marmottant, S. Hilgenfeldt, *Nature* **423**, 153, 2003.)

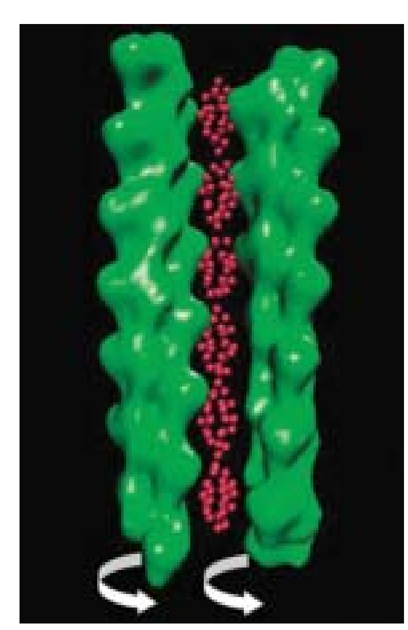


A PICOSECOND-RESOLUTION CRYSTALLOGRAPHIC MOVIE OF A FUNCTIONING PROTEIN has been created by a multinational collaboration. Crystallographers have amassed snapshots of thousands of frozen proteins, but those structure determinations provide only limited information on how a protein actually works. It would be more informative to capture a protein's full collection of motions as it functions (see the article by Eric Galburt and Barry Stoddard in *Physics Today*, July 2001, page 33). Now, using the European Synchrotron Radiation Facility in Grenoble, France, researchers have made picosecond movies of a mutant form of myoglobin—the protein that stores oxygen in muscle tissue—ridding itself of a toxic carbon monoxide molecule. To capture this process, the scientists first hit the protein with a 1-ps pulse of laser light to dislodge the CO, then used an intense 150-ps x-ray pulse with a variable time delay. A CCD camera recorded the diffraction pattern at each time delay; from that recording, the collaborators deduced the sequence of the rapid structural changes. The movie showed the CO migrating to various sites in the protein, with the myoglobin rearranging its shape accordingly. The picosecond time scale of the structural changes is similar to the time scale of many molecular dynamics simulations, and could allow for closer comparison between theory and experiment. (F. Schotte *et al.*, *Science* **300**, 1944, 2003.)

TUMOR FLY-THROUGH MOVIES. Researchers at Purdue University and the Imperial College of Science in London have created a real-time holographic system to acquire a fly-through movie of living tissue using infrared light and a special, semiconductor holographic film. The acquired images showed structure inside rat tumors that, with conventional techniques, would only be visible if the tumor was sectioned into thin slices or imaged with ionizing radiation. The researchers created the fly-through movie using optical coherence imaging (OCI). OCI is related to the more widely known optical coherence tomography (OCT). However, OCT involves scanning a laser beam through a sample and gathering information point by point, which then must be assembled into a complete image. OCI, on the other hand, captures complete images of thin tissue sections that can be recorded directly with a video camera. The key to the holographic OCI technique is a dynamic holographic film that filters out the scattered, incoherent background light but passes the coherent, full-frame images to a camera. Tissue readily reflects image-bearing infrared light, but it also strongly scatters the light, and without coherence filtering the scattered light would overwhelm the coherent pictures. By adjusting the relative delay between the image beam and the reference beam in the OCI system's imaging interferometer, the researchers could control the depth of the images and assemble a slice-by-slice tour through a tumor while leaving the tissue intact. Application of the OCI technique to cultured rat tumors revealed structures that appeared to be necroses (regions of dead tissue) and calcifications much like those found in human cancers. Ultimately, the researchers explain, holographic OCI could offer a nondestructive alternative to x-rays and microsectioning methods for studying living tissue. (P. Yu *et al.*, *Applied Physics Letters*, 21 July 2003.)

THE ATTRACTION OF LIKE-CHARGED BIOMOLECULES to each other is beginning to yield its secrets. The like-charge attraction occurs with polyelectrolytes, large molecules that have a net electric charge in an aqueous solution. (See the article by William Gelbart, Robijn Bruinsma, Philip Pincus, and Adrian Parsegian in *Physics Today*, September 2000, page 38.)

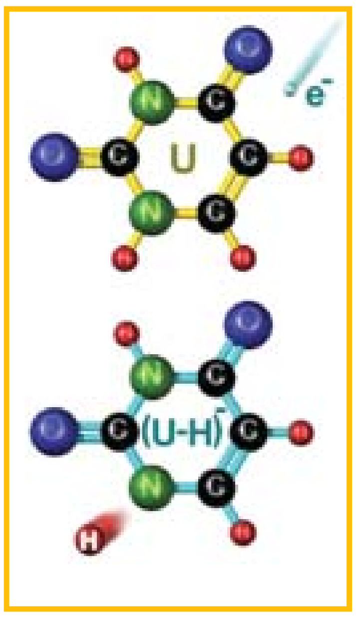
Researchers have long recognized the importance of multiply charged counterions—small dissolved ions having the opposite sign of charge—as the biomolecule of interest. Now, a group of experimenters led by Gerard Wong (University of Illinois at Urbana-Champaign) has investigated the role of counterions in a series of experiments.



They found that charged filamentary actin molecules could self-organize into an unexpected liquid-crystal phase—a stack of two-dimensional rafts—and that divalent (doubly charged) ions provided the crucial cross-linking between both the filaments and the rafts. Divalent ions of magnesium, calcium, strontium, and barium all worked (the figure shows two actin molecules attracted through the intervention of Ba ions, represented as red dots). The ion-induced changes may play an important role in the restructuring and regulation of the cytoskeleton. Studying counterions fashioned from dumbbell-shaped divalent molecules with variable lengths, Wong's group found that the most effective ones were the smallest. Since the effective screening length can approach molecular dimensions, the smallest ions could fit within the "screening sheath" and create a localized charge inversion that promoted attraction.

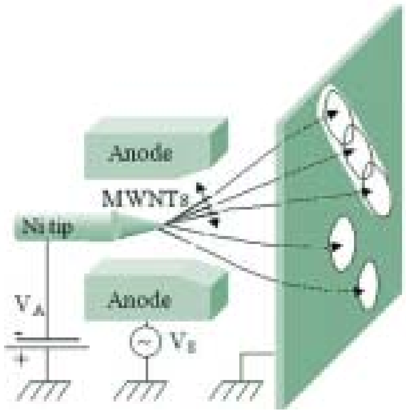
The larger dumbbells could not, and behaved like two separate monovalent ions. Working again with filamentary actin, Wong and colleagues found that counterions organize themselves into columns and form frozen counterion-density waves between the protein rods. Remarkably, the tiny ions induce the large actin molecules to twist, which facilitates like-charge attractions. (G. C. L. Wong *et al.*, *Phys. Rev. Lett.* **91**, 018103, 2003; J. C. Butler *et al.*, *Phys. Rev. Lett.* **91**, 028301, 2003; T. E. Angelini *et al.*, *Proc. Natl. Acad. Sci. USA* **100**, 8634, 2003.)

ULTRA-LOW-ENERGY ELECTRONS CAN BREAK UP URACIL, a new study shows. How injurious is radiation (alpha, beta, and gamma rays or heavy ions) to living cells? This important question has been addressed in many ways. Much attention has centered on the secondary particles produced in the wake of the intruding primary radiation, especially electrons (about 40,000 electrons are produced for each MeV of energy deposited) with typical energies of tens of electron volts. Many of these secondary particles quickly lose their energy and become attached (solvated) to water molecules in the cell. What is the general effect of electron energies below 20 eV? A report from three years ago (Boudaiffa *et al.*, *Science* **287**, 1658, 2000) showed that electrons in the 3-20 eV range are able to produce substantial genotoxic damage, including breaking single- and double-stranded DNA. What about secondary electrons with even smaller energies? To look at this energy range for the first time, Tilmann Maerk and his colleagues at the Universitat Innsbruck (Austria) and the University Claude Bernard Lyon (France) scattered a beam of sub-eV electrons from a beam of gaseous uracil molecules. Uracil is one of the base units of RNA molecules, and is thus a crucial component in cells. These scientists found that uracil is efficiently fragmented by electrons with energies as small as milli-electron-volts. It's not the electron's kinetic energy that causes the disruption, but the electron's charge, which changes the uracil's internal potential energy environment. Furthermore, in the process a very mobile atomic hydrogen can be freed, which on its own, as a radical (a free chemical unit by itself), can do damage to biomolecules. Maerk says that this low-energy damage seems to be a general result since his group has since performed similar work with thymine (a DNA base) and have seen similar fragmentation. (Hanel *et al.*, *Phys. Rev. Lett.* **90**, 188104, 2003)



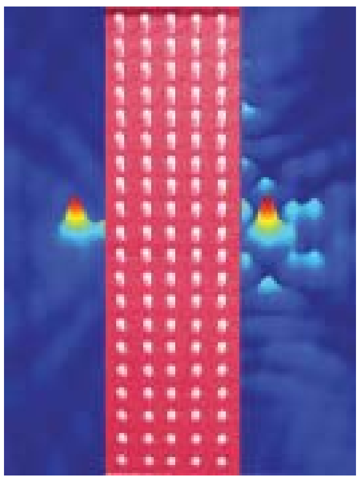
CONDENSED MATTER/MATERIALS PHYSICS

CARBON NANOTUBE RESONANCE FREQUENCIES can be tuned by a factor of 10 in a field-emission microscope (FEM). A group of physicists at the University of Lyon, France, grew several multiwall nanotubes (MWNTs) on a nickel support tip, then placed the tip in an FEM. With a static voltage applied between the nanotubes and a counter electrode, electrons sprayed out of the MWNTs onto a detection screen. Each MWNT has natural resonant frequencies at which it oscillates with large amplitudes. The vibration is excited by applying an additional sinusoidal voltage of the correct frequency to one of the electrodes (*see figure*). By varying the applied voltage and watching the screen, the researchers not only measured the natural resonances for several MWNTs—permitting a measure of the MWNT stiffness—but also found that the voltage effectively "pulls" on the nanotube, tuning it much like increasing the tension on a guitar string. According to group member Stephen Purcell, carefully excited and tuned MWNTs may act as a core element for future nanometric oscillator circuits, nanobalances, or nanoforce sensors. For more on carbon nanotubes, see articles in *Physics Today* by Thomas Ebbesen (*Physics Today*, June 1996, page 26) and by Cees Dekker (May 1999, page 22). (S. T. Purcell *et al.*, *Phys. Rev. Lett.* **89**, 276103, 2002.)

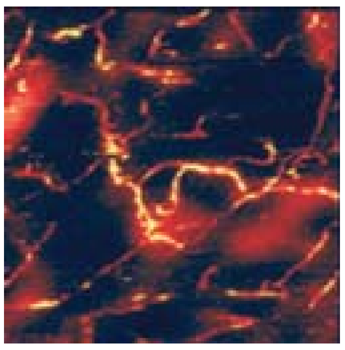


THE GIANT PLANAR HALL EFFECT is a new type of magnetoresistance (MR) seen in a ferromagnetic semiconductor by a team of physicists from Caltech and the University of California, Santa Barbara. In the usual Hall effect, current flowing along a planar conductor is slightly swept to the side when a magnetic field, oriented perpendicular to both the current and the plane, is turned on. In the new experiment, the applied magnetic field lies in the conducting plane, at some angle to the current. The physicists found that, for all nonzero angles—except those aligned with directions of high crystallographic symmetry—there were always two large and abrupt jumps in the Hall voltage as the magnetic field strength was varied. This type of anisotropic MR switching behavior was previously seen in magnetic metals, but the effect in the magnetic semiconductor (GaMnAs) is a factor of 10^4 stronger. MR effects are important in the huge magnetic read-head industry and are also central to the development of spintronics, in which an electron's spin, not just its charge, is instrumental in carrying out high-speed operations. (H. X. Tang *et al.*, *Phys. Rev. Lett.* **90**, 107210, 2003.)

LEFT-HANDED MATERIALS ARE NOW BEING EXPLORED EXPERIMENTALLY. LHMs—which do not exist in nature—have a negative index of refraction, $n < 0$, meaning that light entering such a material at an angle is refracted on the same side of the normal as its incidence. In principle, an LHM with $n = -1$ can perfectly focus light without any curved surfaces. The first composite LHMs were built three years ago (see *Physics Today*, May 2000, page 17, and June 2001, page 9), but some aspects of the theory were controversial. At the March 2003 meeting of the American Physical Society in Austin, Texas, two more labs reported devising LHMs and beginning to study the bizarre properties of such materials. Andrew Houck from MIT reported that microwaves refracted through a wedge-shaped LHM "prism" indeed obeyed Snell's law with a negative n: The microwaves never crossed the normal. The MIT group also provided preliminary evidence that light from a point source can be focused with a flat rectangular LHM slab. Technically, only the real part of n must be negative in an LHM. Patanjali Parimi from Northeastern University in Boston reported measurements of both the real and imaginary parts not only of the index of refraction, but also of the permittivity and permeability of an LHM sample in a microwave waveguide. (The image, from Northeastern, shows a stylized representation of a LHM that acts as a flat lens.) The prediction of perfect focusing can only be realized when the imaginary part of n, which represents absorptive losses, is zero. (A. A. Houck, J. B. Brock, I. L. Chuang, *Phys. Rev. Lett.* **90**, 137401, 2003. P. V. Parimi *et al.*, *Nature* **426**, 404, 2003)

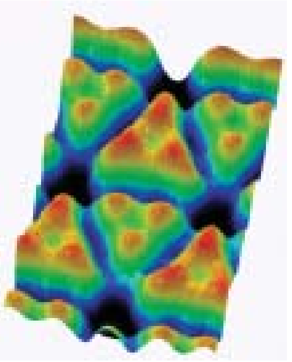


OPTICAL NEAR-FIELD RAMAN MICROSCOPY of single-walled carbon nanotubes has been done. Scientists from the University of Rochester, Portland State University, and Harvard University combined near-field optics, surface-enhanced Raman scattering (SERS), and scanning probe techniques to achieve 25-nm resolution images using 633-nm laser light. The researchers fashioned a silver wire with an extremely sharp (10-15-nm radius) tip and placed it within about 1 nm of the sample, in this case a nanotube. When they directed the laser light to the tip, SERS took over: A greatly enhanced electric field at the tip excited the nanotube, which, in turn, emitted photons that were collected in the far field and analyzed. By scanning the tip over the sample, images like the one shown here were built up. The image is chemically specific—the only frequencies of light emitted correspond to vibrational excitations of the molecule being studied—and can be combined with spectroscopy. The researchers hope that better resolution will allow them to obtain detailed pictures of proteins in cell membranes. (A. Hartschuh *et al.*, *Phys. Rev. Lett.* **90**, 095503, 2003.)



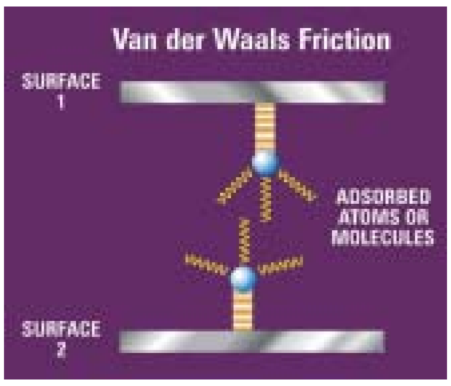
SUPER-TOUGH AND LONG COMPOSITE FIBERS MADE OF CARBON NANOTUBES. Scientists at the University of Texas at Dallas injected a dispersion of single-walled CNTs into a pipe filled with a flowing polyvinyl alcohol solution to spin 100-m-long gel fibers, which were then converted into solid fibers having a tensile strength of 1.8 gigapascals. Tougher than spider silk, Kevlar7, or graphite fibers, the 50-μm-diameter composite fibers are 60% CNT by weight. The researchers also made their fiber into a "supercapacitor" and incorporated it into a woven fabric. (A. B. Dalton *et al.* , *Nature* **423,** 703, 2003.)

AN ENERGY-FILTERED SCANNING TUNNELING MICROSCOPE (EF-STM). A typical STM yields atomic-scale landscapes of electrically conducting surfaces by mapping the electronic states closest to the Fermi energy, εF. Now, physicists at the Colorado School of Mines have used a semiconductor tip (indium arsenide) on an STM to selectively image electronic states of various energies. Their EF-STM works by effectively suppressing tunneling in a range of energies within the "projected bandgap" along the tip's axis. Changing the bias voltage on the tip shifts the gap relative to the sample's states and allows electrons with different energies to tunnel. On a silicon surface, the researchers separately mapped dangling bonds from both the silicon adatoms, which have electron energy close to εF and are seen by conventional STMs, and the silicon atoms in the second layer, which have electron energies further below εF. Shown is an energy-filtered image which captures atoms with lower-energy electrons (seen in red) which would ordinarily be obscured by normal STM methods. The group foresees the ability to map the local composition of semiconductor alloys. (P. Sutter *et al.*, *Phys. Rev. Lett.* **90**, 166101, 2003.)

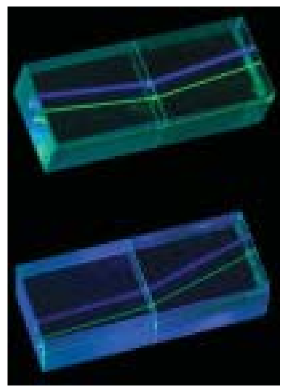


ENTANGLED PROTONS IN A SOLID POLYMER. In condensed matter systems, adjacent nuclei and their nearby electrons can all, in principle, be in a state of quantum entanglement, but the decoherence time would be exceedingly short—in the subfemtosecond realm. Still, the effect could be observable, according to Aris Chatzidimitriou-Dreismann (Technical University Berlin), because the time scale is roughly the same as the interaction time for Compton scattering. Several years ago, he performed neutron Compton scattering off water molecules and saw an anomalous shortfall of scattering from protons, which he attributed to short-lived nuclear entanglement. Now, he and his collaborators have Compton-scattered both neutrons and electrons off protons in a polymer called formvar. The electron experiments, done at the Australian National University in Canberra, showed precisely the same shortfall as the neutron experiments, done at the ISIS neutron spallation source in the UK. The similarity of the results is striking because the two projectiles interact with protons via fundamentally different forces—electromagnetic and strong. (C. A. Chatzidimitriou-Dreismann *et al.*, *Phys. Rev. Lett.* **91**, 057403, 2003.)

NONCONTACT FRICTION CAN BE ENHANCED BY PHOTON TUNNELING. Usually, two bodies in relative motion feel friction when the respective surface atoms are in contact. In contrast, noncontact friction is similar to the van der Waals force, a common but weak attractive force that arises when an atom or molecule spontaneously develops an electric dipole moment due to a thermal or quantum fluctuation. The short-lived atomic polarity can induce a dipole moment in a neighboring atom or molecule some distance away. A new study of van der Waals friction by theorists Alexander Volokitin and Bo Persson of the Institute of Solid-State Research at Germany's Research Center Jülich found that when surfaces are separated by about 1 nm, the van der Waals friction can be greatly enhanced in three ways. First, they found that the friction increases a 100-fold or more when two clean conducting surfaces move toward or away from each other rather than in parallel relative motion. The other two effects involve resonant photon tunneling. For semiconductor surfaces, photon tunneling can generate surface plasmons whose interaction can increase the noncontact friction by several orders of magnitude. And resonant tunneling between vibrational modes of adsorbate atoms on otherwise clean conducting surfaces (depicted in the figure) can enhance the van der Waals friction over that of the clean surfaces alone. The adsorbate atoms act like tiny antennas: When the emitters and receivers are in tune, their electromagnetic interaction is greatly enhanced. The researchers' calculation showed a seven-orders-of-magnitude enhancement for this effect, consistent with previously unexplainable experimental results with scanning tunneling microscope probes. (A. I. Volokitin, B. N. J. Persson, *Phys. Rev. Lett.* **91**, 106101, 2003.)



NEGATIVE AND POSITIVE REFRACTION AT THE SAME CRYSTAL INTERFACE has been demonstrated. In negative refraction, which takes place in "left-handed materials" (LHMs), a light ray impinging on an interface never crosses the normal to that interface. Until now, all LHMs have been so-called metamaterials composed of rods and split-ring resonators mounted on boards (see *Physics Today*, May 2000, page 17, and the second correction in July 2000, page 77). Now, physicists at the National Renewable Energy Laboratory in Golden, Colorado, have found a class of LHMs made from bicrystals that display a certain "domain twin" structure. Such a structure occurs in both natural and easily engineered ferroelastic materials and is shown here in an electron micrograph of a III-V semiconductor alloy with copper-platinum ordering. The researchers used a single YVO_4 bicrystal to demonstrate, depending on the angle of incidence, both positive and negative refraction (see image). What's more, the schizophrenic—called amphoteric—refraction occurred for ballistic electrons as well as for light and suffered no losses to reflection at the interface. (Y. Zhang, B. Fluegel, A. Mascarenhas, *Phys. Rev. Lett.* **91**, 157404, 2003.)

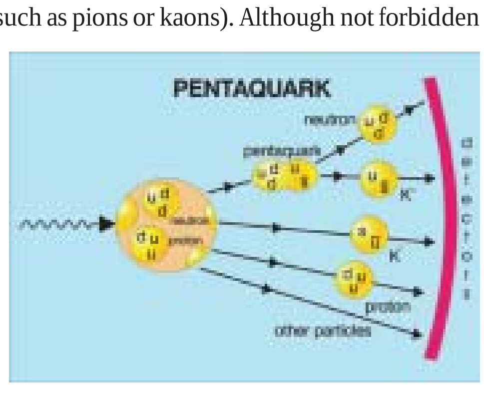


HIGH-PRESSURE PHOSPHOROUS COULD BE USEFUL FOR SPINTRONICS. Found in teeth and bones as well as in fertilizers and DNA, phosphorus is an insulator at room temperature. However, at very high pressures, a series of phase transitions occur. At 10 GPa, phosphorous becomes metallic and can superconduct at about 10 K. At 262 GPa, it takes on a body-centered-cubic (bcc) crystal structure. Now, Sergey Ostanin of the University of Warwick in the UK and his colleagues have studied the high-pressure phase diagram of phosphorous, and calculated that the bcc crystals achieve superconductivity at slightly higher temperatures, somewhere around 20 K. Furthermore, they found that the bcc phase might be stabilized in thin films grown at ambient pressure on some other bcc material. Such a phosphorous film, perhaps sandwiched between films of iron, might be very useful in spintronics applications. For example, a superconducting spin switch could flip-flop from superconductor to regular conductor depending on the spin state of the iron films. (S. Ostanin *et al.*, *Phys. Rev. Lett.* **91**, 087002, 2003.)

SHOCKING COLOR EFFECTS. A photonic crystal is a lattice of structures (sometimes an arrangement of rods or a solid filled with a pattern of holes) with a periodic alteration in the index of refraction. In such a material waves with only a select band of frequencies may propagate successfully. Other frequencies are forbidden. What happens, though, when a shock wave moves through the lattice, momentarily compressing or expanding the characteristic spacings? A new "computational experiment" (detailed computer simulation) provides an intriguing answer. Evan J. Reed, Marin Soljacic, and John Joannopoulos at MIT determine that a light beam moving in a shock-modified photonic crystal will undergo two unexpected changes: a Doppler shifting hundreds or even 10,000 times bigger than usual and a bandwidth narrowing. There are plenty of phenomena that can broaden a signal's bandwidth but none yet known that would narrow the bandwidth of an arbitrary signal in this way (and by factors of 4 or more). As for the Doppler shift (a change in the frequency of the light owing to its reflection from a moving target), the light reflecting from the shock wave can be "up converted" (*e.g.*, turned from red light into green light) with an efficiency that should match or exceed the up conversions achieved with nonlinear optical materials. Furthermore, the shock conversion process is tunable and independent of light intensity. According to Evan Reed, the MIT research should generate great surprise and interest among those who work with photonic crystals. The next step will be to implement the computational results in the laboratory with samples and actual shock waves, although for the sake of eventual commercial applications (frequency conversion and signal modulation) future modifications in photonic crystals will not have to be initiated with guns or laser pulses but with less destructive acousto optic effects. The photonic crystal modulations might even be actuated with some kind of MEMS (microelectromechanical systems) device. (Reed *et al.*, *Phys. Rev. Lett.* **90**, 203904, 2003; website http://ab-initio.mit.edu)

PARTICLE/NUCLEAR/PLASMA PHYSICS

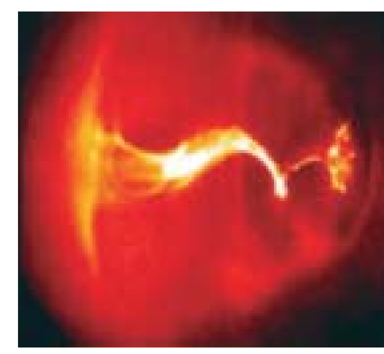
A FIVE-QUARK STATE has been discovered. It was first reported by a group of physicists working at the SPring 8 physics lab in Japan but has been found at other labs too. All confirmed particles known previously have been either combinations of three quarks (baryons, such as protons or neutrons) or two quarks (mesons such as pions or kaons). Although not forbidden by the standard model of particle physics, other configurations of quarks had not been found until now. But a larger quark grouping was hypothesized by theorists at the Petersburg Nuclear Physics Institute in Russia (D. Diaknov, V. Petrov, M. Polyakov, *Z Phys. Rev. A* **359**, 305, 1997). The subsequently observed "pentaquark" particle, with a mass just above 1.5 GeV, was discovered in the following way. At the SPring 8 facility a laser beam is scattered from a beam of 8-GeV electrons circulating in a synchrotron racetrack. These scattered photons constitute a beam of powerful gamma rays which were scattered from a fixed target consisting of carbon-12 atoms. The reaction being sought was one in which a gamma and a neutron inside a carbon nucleus collided, leaving a neutron, a K+ meson, and a K meson in the final state. (The image shows the stream of particles that are created in the high-energy collisions.) Efficient detectors downstream of the collision area looked for the evidence of the existence of various combinations of particles, including a short lived state in which the K+ and the neutron had coalesced. In this case the amalgamated particle, or resonance, would have consisted of the three quarks from the neutron (two "down" quarks and one "up" quark) and the two quarks from the K+ (an up quark and a strange antiquark). The evidence for this collection of five quarks would be an excess of events (a peak) on a plot of "missing" masses deduced from K particles seen in the experiment. The Laser Electron Photon Facility (LEPS) at the SPring 8 machine reported exactly this sort of excess at a mass of 1540 MeV with an uncertainty of 10 MeV. The statistical certainty that this peak is not just a fluctuation in the natural number of background events, and that the excess number of events is indicative of a real particle, is quoted as being 4.6 standard deviations above the background. This, according to most particle physicists, is highly suggestive of discovery. (Nakano *et al.*, *Phys. Rev. Lett.* **91**, 012002, 2003) Confirmation of this discovery comes quickly. A team of physicists in the US, led by Ken Hicks of Ohio University working in the CLAS collaboration at the Thomas Jefferson National Accelerator Facility, has also found evidence for the pentaquark, which is now referred to as the Theta particle. A photon beam (each photon being created by smashing the Jefferson Lab electron beam into a target and



then measuring the energy of the scattered electron in order to determine the energy of the outgoing gamma) was directed onto a nuclear target. The photon collides with a deuteron target and the neutron kaon (nK^+) final state is studied in the CLAS detector. The CLAS group reported that the mass measured for the pentaquark, 1.543 GeV with an uncertainty of 5 MeV), is very close to the LEPS value. The statistical basis of the CLAS measurement is 5.4 standard deviations (S. Stepanyan *et al.*, hep-ex/0307018). Evidence has also been found at the ELSA accelerator in Bonn (J. Barth *et al.*, hep-ex/0307083), and in old Russian bubble chamber data (V. Barmin *et al.*, hep-ex/0304040). (See also *Physics Today*, September 2003.)

CHARGE SYMMETRY BREAKING (CSB) has been observed in two experiments, reported in April 2003 at the American Physical Society meeting in Philadelphia. In the 1930s, Werner Heisenberg proposed that the neutron and proton are slightly different manifestations of the same particle, the "nucleon." Modern nuclear physics endorses this view: Many nuclear reactions proceed exactly the same if a proton replaces a neutron, or vice versa. However, the similarity of protons and neutrons breaks down in some cases, leading to CSB. Edward Stephenson of Indiana University announced the first unambiguous identification of a process that is forbidden if charge symmetry is exact: the fusion of two deuterium nuclei to form a helium nucleus and a neutral pion. The experiment was conducted over a two-month period at the Indiana University Cyclotron Facility (E. J. Stephenson *et al.*, *Phys. Rev. Lett.* **91** , 142302, 2003). Allena Opper of Ohio University discussed the other result: the fusion of a proton and neutron to form a deuteron and a neutral pion (A. K. Opper *et al.*, *Phys. Rev. Lett.* **91**, 212302, 2003) The experiment—a collaboration at the TRIUMF cyclotron in Canada—revealed a hallmark of CSB: A small excess of deuterons emerged in a preferred direction. CSB has been observed many times before, but the new results promise a wealth of information on such things as the slightly different electromagnetic fields inside each nucleon and why the neutron and proton have slightly different masses. The results can also potentially yield more precise values of the mass difference between the up and down quarks that make up protons and neutrons.

THE TWISTED ORIGIN OF SPHEROMAKS. Researchers at the California Institute of Technology have made important progress in solving a long standing mystery concerning the formation of spheromaks, self organizing toroidal plasma configurations that are superficially reminiscent of smoke rings. It is well known that current carrying plasmas embedded in an initial seed magnetic field can form spheromaks. The formation process is believed to involve some kind of dynamo process, whereby the internal magnetic fields become rearranged or even amplified so as to achieve a stable minimum energy state for the internal magnetic forces. But until now, no one has definitively demonstrated just how a plasma transforms from an unstable, high internal energy configuration into a spheromak. The new experiment sheds light on the phenomenon by capturing images of plasmas as spheromaks form. The images show that plasma currents initially flow in straight lines along a confining magnetic field. Owing to an effect known as the kink instability, the plasma currents develop bends that twist into a helix. The helix acts like a coiled current element, or solenoid, which amplifies the original, straight magnetic field. Above a certain threshold in the initial magnetic field, detached plasma spheromaks are formed. The researchers confirmed the theory behind the effect by measuring the rapid amplification of the magnetic field inside developing plasma solenoids. Spheromaks are potentially promising routes to plasma based nuclear fusion, and insight into their formation will help in the design of future experiments and possibly even a clean, safe energy source. In addition, spheromak formation is important for explaining the behavior of plasma in the solar corona, as well as understanding the physics of jets that sprout from black holes, galactic nuclei, and other astrophysical objects. (S. C. Hsu and P. M. Bellan, *Phys. Rev. Lett.* **90**, 215002, 2003)



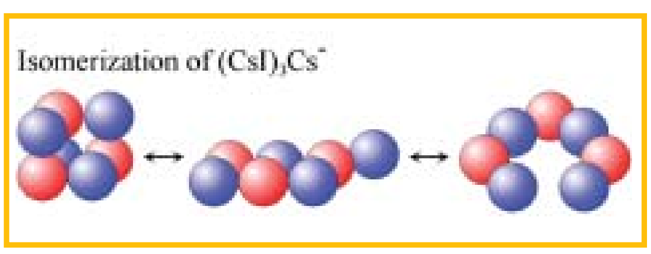
FIRST FUSION AT THE Z MACHINE was announced at the April 2003 meeting of the American Physical Society in Philadelphia. For the first time, Sandia National Laboratory's Z facility in New Mexico, created a hot dense plasma that produces neutrons associated with nuclear fusion. According to Sandia's Ray Leeper, the neutrons emanate from fusion reactions within a BB sized deuterium capsule placed within the central target in the Z facility, itself about a third of a football field in diameter. While tokamaks cause fusion reactions to occur by confining plasmas in large magnetic fields, and laser facilities focus intense beams on or around a target, Z applies a huge pulse of electricity (about 12 million joules) with very sophisticated timing. The pulse creates an intense magnetic field which crushes an array of 360 tungsten wires into an ultra-light foam cylinder to produce x-rays. Striking the surface of the fuel capsule embedded in the cylinder, the x-ray energy produces a shock wave that compresses deuterium gas within the capsule, fusing enough deuterium to produce neutrons. Sandia researchers measured a yield of approximately 10 billion neutrons, around the expected energy of 2.45 MeV, corresponding to a very modest level of nuclear fusion (about 4 millijoules of energy). The deuterium capsule reached a temperature of about 11.6 million Kelvin and was compressed from a diameter of 2 mm to 160 microns. The whole compression took about 7 nanoseconds. Providing outside commentary, Cornell University's David Hammer said the Sandia group performed pretty much a full set of tests to verify that they had achieved nuclear fusion. The ZR (Z Refurbished) facility, an upgrade scheduled to go online in 2006, is slated to attempt scaled up fusion experiments. While the Z approach to fusion is a promising, straightforward, and potentially robust method, researchers caution that they are at the start of a very long road in investigating its feasibility as a fusion power source.

PLASMA WAKEFIELDS ACCELERATE POSITRONS. An experiment conducted at SLAC features a number of firsts: the first time positrons have been accelerated by the plasma wakefield method; for the first time wakefield acceleration has been achieved with meter size plasmas (previous efforts have taken place in 10 cm cells); and the first to operate under realistic accelerator conditions (in this case a 30 GeV beam of positrons). In this UCLA/SLAC/USC collaboration, positron bursts are sent into a 1.4 meter long chamber filled with a lithium plasma. The first two thirds of the burst sets up powerful electric fields in the plasma which then serve to accelerate the trailing one third of the burst to higher energy. The boosted positrons increased their energy by about 80 MeV over a length of 1.4 m, for an acceleration gradient of about 50 MeV/m. This is comparable to the best acceleration that can be accomplished with conventional RF techniques in which electrons or positrons are taken up to higher energies by soaking up radio energy coupled into the beam pipe. But the wakefield researchers expect that the gradient can be enhanced a hundredfold to 5 GeV/m if the size of the beam pulses can be shrunk by a factor of 10. According to Chan Joshi of UCLA the wakefield approach may not be fully mature by the time the next electron positron collider is built, but its benefit could be tested by installing two plasma accelerator sections, one for positrons and one for electrons, just before the interaction point for some final energy boosting in an existing collider. (M. J. Hogan *et al.*, *Phys. Rev. Lett.* **90**, 215002, 2003.)

OTHER PHYSICS FIELDS

ICICLE INSTABILITY. No two snowflakes are alike, according to common wisdom. Icicles, on the other hand, are all alike that is, the ripples that embellish the surfaces of most icicles are similar regardless of variations in air temperature, humidity, icicle thickness, or growth rate. An icicle grows when thin sheets of water flow down the icicle shaft. A portion of the flowing water freezes and the rest drips from the icicle tip. But the ice that's left behind doesn't build up uniformly; instead, it is selectively deposited at certain locations.

As a result, icicles are covered in ring like ripples extending along their lengths, which always measure about 1 cm from peak to peak. Researchers at Hokkaido University's Institute of Low Temperature Sciences in Japan have developed a theoretical model that explains the surprisingly universal structure of icicles. According to the new model, two effects are important as an icicle grows. The first effect is the Laplace instability, which is related to the latent heat released from an icicle's surface and dispersed into the air through the thin water layer. The instability arises because heat is more rapidly lost from the convex surfaces than that from the concave surfaces, which makes ice build up faster on an icicle's convex protrusions than on the concave indentations, thus amplifying ripples. The second factor is the fluid effect. Flow in the thin water layer decreases the temperature distribution along the layer, making it uniform and thus inhibiting the Laplace instability. As it happens, these two competing effects ensure that all icicle ripples have the same wavelength, although the ripple height can vary from one icicle to another. The theory also predicts that the ripples should migrate down an icicle at about half the speed that the icicle grows a prediction the researchers hope will soon be verified experimentally. In addition the researchers expect that their model should be helpful in explaining the structures of mineral stalagmites commonly found in limestone caves. (N. Ogawa and Y. Furukawa, *Physical Review E*, **66** 041202,2002)



SALT: THE MOVIE. Solid, liquid, melting, and freezing are concepts that refer to bulk matter, not to individual atoms. But what about a small cluster of atoms or molecules? Louis Bloomfield and Andrew Dally (University of Virginia) looked at a pulsed beam of clusters of a salt; each cluster contained dozens of molecules that each had four cesium atoms and three iodine atoms. An ordinary salt grain has more than a million atoms along each side of its cubical structure. The Cs_4I_3 molecule can take on three different shapes or "isomers": a cube, ladder, or ring (shown in the figure). The researchers sent the salt clusters through a laser interaction region, where the cubic isomer was depleted. Using probing lasers downstream, the researchers watched at a cinematic 30 "frames" per second as the population of the cubic form was restored at the expense of ladders and rings. The interconversion, known as isomerization, happened more quickly with higher temperature. In fact, at about 500 K, the molecules spent only enough time in any one shape to convert into another, the signature of a phase transition from solid to liquid in a bulk system. Interestingly, the melting temperature of bulk cesium iodide is about 900 K. (A. J. Dally, L. A. Bloomfield, *Phys. Rev. Lett.* **90,** 063401, 2003.)

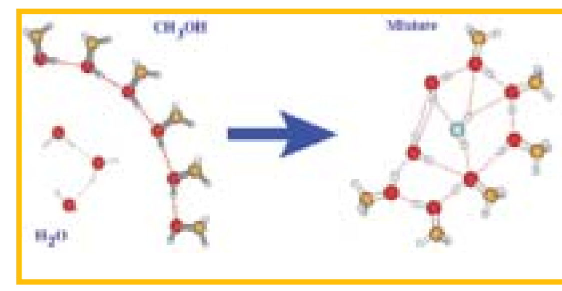
A "WATER HAMMER" POWERS UP SONOLUMINESCENCE. In household plumbing, a water hammer can occur when a sudden slowdown of the water's flow generates a temporary vacuum and a shock wave that together violently shake the piping. Now, Seth Putterman of UCLA and his colleagues have used a water hammer to generate sonoluminescence (SL), bursts of light from collapsing bubbles.

The researchers vertically shook a 60-cm-tall, 4-cm-diameter cylindrical tube—containing a small amount of xenon gas dissolved in water—with an acceleration of 2g. During a shake cycle, bubbles formed and collapsed sporadically and produced as many as 3×10^8 photons (about a hundred times more than earlier SL experiments). That emission corresponds to a peak power of almost half a watt. (C.-K. Su *et al.*, *Phys. Fluids* **15**, 1457, 2003.)

NANOSCOPIC THERMOMETER. A nanoscopic thermometer, consisting of a magnesium oxide nanotube filled with gallium metal, may dramatically increase the temperature range of tiny thermometers. Researchers at the National Institute for Materials Sciences announced the creation of a carbon nanotube thermometer last year, but the device had at least one shortcoming: nanoscopic carbon tubes rapidly degrade in air at temperatures of 600 -700 degrees Celsius. The new nanotubes are made of magnesium oxide cylinders with inner diameters of 20-60 nanometers, or about a thousandth the thickness of a human hair. Magnesium oxide nanotubes, in contrast to carbon versions, can withstand high temperatures. Often, there is a gap in a nanotube's gallium filling, and because gallium expands as it's heated, the temperature of the thermometer is read out by measuring changes in the gap between the two portions of the metal. The tiny thermometers are expected to function well up to about 1000 degrees Celsius. Eventually, miniature thermometers such as these could be important for measuring temperature in the vicinity of nanoscopic motors and other tiny devices. (Y.B. Li, Y. Bando, D. Golberg, and Z.W. Liu, *Appl. Phys. Lett.*, **83**, 4414, 2003)

DETECTING PLASTIC EXPLOSIVES IN AIR at the parts-per-trillion level has been achieved. Explosive compounds such as PETN and RDX are easy to mold, remain stable until detonated, and can inflict significant damage even in small amounts. Now, researchers at Oak Ridge National Laboratory and the University of Tennessee, Knoxville, have reported using commercially available atomic force microscope cantilevers for detecting PETN and RDX with great sensitivity. One surface of the cantilever was coated with a monolayer of 4-mercaptobenzoic acid, which can bind to both PETN and RDX. As the binding occurs, the cantilever bends significantly due to differential stress. The researchers estimate that a sensor based on their technique could detect the explosives at a level of 14 parts per trillion after only 20 seconds of operation. Such a sensor is also potentially cheap and easy to mass-produce. (L. A. Pinnaduwage *et al.*, *Appl. Phys. Lett.*, **83**, 1471, 2003.)

VIBRATIONS HELP A FROG LOCATE TASTY PREY. Living in southern Africa, the aquatic clawed frog *Xenopus laevis laevis* finds insects by localizing their vibrations on the water's surface. Hunting at night and unable to see well, the frog gets a wealth of information from about 180 sensory organs (the white "stitches" in the photo, collectively called the lateral-line system) on its skin. As an insect sloshes around, the moving water triggers signals in hair cells attached to the organs. Now, researchers in Germany, led by Leo van Hemmen (Technical University of Munich), have developed a simple model, with a minimal set of assumptions, that explains how the lateral-line system works. Strikingly, the model suggests that the frog can both reconstruct the waveform of the water disturbance and determine its direction. The model thus explains the frog's ability to distinguish between two different water disturbances coming simultaneously from insects—one of which might be inedible—in different directions. The model also agrees with experiment in showing that the sensory system can operate even if some of the lateral-line organs do not function properly. The researchers' model may also be applicable to the mechanosensory systems of other animals, such as fish and crocodiles, which have similar receptor organs (J.-M. P. Franosch *et al.*, *Phys. Rev. Lett.* **91**, 158101, 2003.)



WHY DON'T ALCOHOL AND WATER MIX VERY WELL? A US-Swedish collaboration has obtained new molecular-level details of mixtures of water and methanol, the simplest alcohol. At Lawrence Berkeley National Laboratory's Advanced Light Source, the researchers used x-ray emission and x-ray absorption spectroscopy to study, for example, the chemical bonds that form between molecules in the liquid over timescales of picoseconds and femtoseconds. In pure methanol, they observed rings and chains made of both six and eight methanol molecules. When the methanol and water were mixed, the molecular rings remained intact. As the figure shows, the CH_3OH chains, however, connected with water molecules to form large, stable water-methanol clusters with a high degree of order, thereby reducing the liquid's overall entropy, which explains the incomplete mixing. To preserve the second law of thermodynamics, only some of the chains are bridged. (J.-H.Guo *et al.*, *Phys. Rev. Lett.* **91**, 157401, 2003.)

THE 2003 PHYSICS NOBEL PRIZE went to Alexei A. Abrikosov (Institute for Physical Problems in Moscow and now at Argonne National Laboratory near Chicago), Vitaly L. Ginzburg (Lebedev Physical Institute, Moscow) and Anthony J. Leggett (University of Illinois, Urbana). The award recognized work done on systems that operate under two regimes very far from human experience: the quantum realm and the low temperature realm. In superconductivity, a current of electrons flowing through a material undergoes a change in behavior: normally reluctant to associate with each other, the electrons at low temperature can form pairs. These pairs act like particles and are so gregarious that they can enter into a single unified quantum state. In this state the electron pairs are no longer just a current, but a "supercurrent." This supercurrent flows without dissipating energy. It flows without resistance. The practical benefit is that energy loss through dissipation can be eliminated. An additional feature is that much higher currents can flow through some superconductor materials than through normal metal wires. The price to pay for producing the weird quantum state of superconductivity in the first place is having to chill the material down to temperature close to absolute zero, which usually means about 4 K. Practical applications of wire made from superconducting material include medical scanners (this year's Nobel for medicine rewards MRI research; here potent magnetic fields inside the scanner are usually produced with superconducting cables), levitated trains (still at an early state of deployment), and the chilling of some components in cell phone networks. In some superconductors (type I) magnetic fields are anathema to the superconducting state. In other superconductors (type II), magnetic fields are tolerated, and this makes possible the applications just mentioned. Abrikosov and Ginzburg are being recognized for their work in explaining how type II superconductors work.

When a sample of helium-3 atoms is chilled to very low temperature, these fermion atoms can pair up, and the pairs in turn may enter into a single quantum state in which (analogous to the loss less flow of supercurrents in superconductors) the fluid will flow without losing energy via friction. Just as superconductors have no electrical resistance, so superfluids have no viscosity, and can flow freely. Leggett is being recognized for his work in explaining He-3 superfluidity. More information on the prize can be found at www.nobel.se and in the December 2003 issue of *Physics Today.*

THE 2003 NOBEL PRIZE IN PHYSIOLOGY/MEDICINE went to Paul C. Lauterbur of the University of Illinois at Urbana Champaign and Peter Mansfield of the University of Nottingham for their work in developing magnetic resonance imaging, or MRI. In the medical world, MRI has become a major imaging technique, but its roots lie in the most basic magnetic physics in the nuclei at the heart of every atom and molecule. Taking advantage of the fact that the body is two-thirds water, MRI obtains images of the hydrogen nuclei in water molecules inside our bodies.

In the early 1970s, while working at the State University of New York at Stony Brook, Lauterbur exploited the magnetic properties of atomic nuclei to yield a two dimensional image of matter, by introducing gradients in the external magnetic field that surrounds the object to be imaged. Shortly thereafter, Peter Mansfield helped to make MRI a practical imaging procedure, in part by coming up with mathematical methods for processing the radio waves released by hydrogen during the technique.

The origins of MRI go back further, to the late 1930s, when physicist I.I. Rabi of Columbia University demonstrated that one could obtain abundant information about lithium chloride molecules by manipulating the magnetic "spins" of the molecules' nuclei (Nobel Prize, 1944). Later, physicists E.M. Purcell (Harvard) and Felix Bloch (Stanford) developed nuclear magnetic resonance (NMR) in hydrogen (Nobel Prize,1952). Two Nobel Prizes in Chemistry (1991 and 2002) have been awarded for achievements in nuclear magnetic resonance. MRI has been so successful that the original technique has spawned numerous offshoots, such as functional MRI (fMRI), which measures brain activity by detecting oxygen levels in specific brain areas. MRI advances continue at a feverish pace. (See www.nobel.se and the December 2003 issue of *Physics Today* for more information on this year's prize.)