repeatedly preparing the state and measuring the states of both atoms. Usually (but not always, because the experiments were imperfect), when the first atom was in $|0\rangle$, the second was in $|1\rangle$, and vice versa. But that observation is not enough to prove entanglement. The atoms could have been produced half the time in the unentangled state $|01\rangle$ and half the time in $|10\rangle$.

A quantum statistical ensemble is characterized by the density matrix ρ. The matrix's diagonal elements $\rho_{k,k}$ are the probabilities P_k of finding the system in state k, where in this case k is one of the four pure states $|11\rangle$, $|10\rangle$, $|01\rangle$, and $|00\rangle$. The off-diagonal element relevant to verifying the entangled state $(|01\rangle + |10\rangle)/\sqrt{2}$ is $\rho_{10,01}$. Called the coherence between $|10\rangle$ and $|01\rangle$, it's a measure of how tightly the phase is constrained between those two components.

The fidelity, $F = (P_{01} + P_{10})/2 + \rho_{10,01}$, quantifies both how close a process comes to reliably producing the state $(|01\rangle + |10\rangle)/\sqrt{2}$ and how much entanglement it produces. When $F > ½$, the atoms are entangled in the sense that their state can't be represented as a statistical ensemble of products of local wavefunctions. (An accessible proof is given in reference 5.) There's a second threshold at $F > \sqrt{2}/2$, corresponding to violation of Bell's inequalities.

In an experiment that entangles the spins of two particles, off-diagonal elements can be measured, and entanglement verified, by measuring the spins in multiple directions. A process that prepares the state $(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/\sqrt{2}$, where $\uparrow$ and $\downarrow$ are the spins in the z direction, produces particles that are opposite in spin in every direction. But if the process randomly produces either $|\uparrow\downarrow\rangle$ or $|\downarrow\uparrow\rangle$, the spins measured in the x direction would appear uncorrelated.

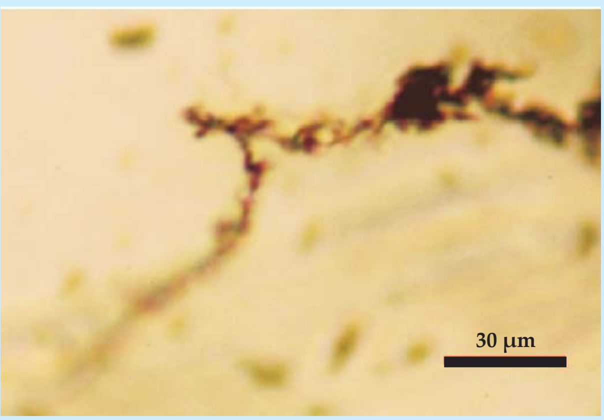
The two-state system that comprises the relevant hyperfine states is mathematically equivalent to a spin-½ particle. Coherent pulses of light do the equivalent of rotating the spins to allow them to be probed in different directions. The Wisconsin researchers ap-

physics update

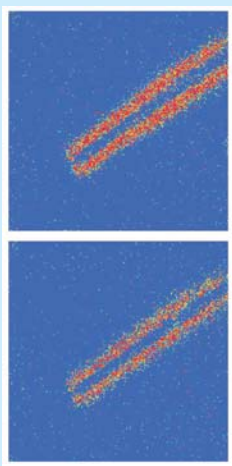
These items, with supplementary material, first appeared at http://www.physicstoday.org.

A carbon halo. In most nuclei the protons and neutrons form a roughly spherical core of approximately uniform density. But along the edges—the so-called drip lines—of the chart of nuclides, a handful of light nuclei have more nucleons than can be accommodated in the nuclear core. The excess, usually one or two neutrons, form a dilute distribution called a halo that extends far beyond the core. At the RIKEN Nishina Center for Accelerator-Based Science, a Japanese team has studied the reaction of heavy carbon nuclei with hydrogen and identified the extremely neutron-rich carbon-22, with its 6 protons and 16 neutrons, as a halo nucleus, the heaviest one yet found. Nuclear radii generally scale as the cube root of the total number of protons and neutrons, yet based on their cross-section data, the researchers calculated the radius of ^{22}C to be twice that of the much more common isotope ^{12}C; indeed, at 5.4 fm it exceeds the radius of lead-208. The halo of ^{22}C comprises two valence neutrons; determining their distribution and other aspects of the halo structure will require experiments with different target nuclei and different beam energies. (K. Tanaka et al., *Phys. Rev. Lett.*, in press.) —RJF

A template for microwire self-assembly. Several methods exist for growing nanowires, whether attached to a substrate or dispersed in a liquid. Using those wires to make designated electrical connections in a circuit, however, has been difficult. Yves Galerne and his colleagues at the University of Strasbourg, France, now demonstrate a procedure that produces conducting wires across a gap between two electrodes. The chemical physicists first paint the electrodes with a polymer so as to create "anchors" in predetermined locations; when the gap is filled with nematic liquid crystals, an isolated defect line—a disclination—connects the anchors and therefore the electrodes. Next, silica particles coated with a conducting polymer are introduced and gather along the disclination like beads on a necklace. In the third step, a voltage across the electrodes welds the necklace beads together into a robust wire. Although ragged with extra polymer aggregates, the central region of a 150-micron-long wire, shown in the photo, demonstrates the team's initial result. The researchers note that the wire's size, smoothness, and conductivity can be improved—for example, by decreasing the silica particles' size and concentration and by electroplating them. (J.-B. Fleury, D. Pires, Y. Galerne, *Phys. Rev. Lett.* **103**, 267801, 2009.) —SGB



Imaging light with electrons. In recent years, notions of the ultrafast, the ultraintense, and the ultrasmall have been recurring themes in physics as those envelopes have been relentlessly pushed to reveal new phenomena. Caltech's Brett Barwick, David Flannigan, and Ahmed Zewail have combined all three notions into a new technique they dub photon-induced near-field electron microscopy. PINEM exploits the fact that free–free interactions of electrons and photons are greatly enhanced when a third body, like a nanostructure, is present and when the electrons are more energetic than the photons. The physicists illuminated a carbon nanotube with an intense femtosecond laser pulse that generated an evanescent plasmonic field at the CNT's surface. Simultaneously, a similar-duration pulse of 200-keV electrons from an electron microscope passed through the sample. During the few-hundred-attosecond interaction time, some of those electrons absorbed energy quanta from the 2.4-eV photon field. By selecting only those electrons that gained energy, the researchers could image the evanescent surface field with the spatial resolution of electron microscopy. That field extends about 50 nm into the vacuum from the dark surface of the roughly



plied $\pi/2$ pulses to both atoms with a variable delay between them; the Paris group irradiated both atoms with a single pulse of variable duration. In both cases, $\rho_{10,01}$ was revealed as the amplitude of oscillation of the parity signal $\Pi = P_{00} + P_{11} - P_{10} - P_{01}$ as a function of that delay or duration. Figure 2 shows the oscillation for the Paris group's experiment.

The Wisconsin group found that their best results came from the H-C_Z CNOT gate, which prepared states with a fidelity of $F = 0.48 \pm 0.06$, just below the threshold for entanglement. The Paris group measured a fidelity of $F = 0.46 \pm 0.06$. But both groups' atoms escaped their traps a significant fraction of the time—17% for the Wisconsin group and 39% for the Paris group—so the measured probability for the system to be in *any* state was less than one. (That's a problem that experimenters who work with ions just don't have to worry about, since loss from ion traps is negligible.) Both groups therefore normalized their results to give the fidelity for only those repetitions of the experiment in which no atoms were lost. For that a posteriori entanglement fidelity, the Wisconsin researchers obtained 0.58, the Paris researchers 0.75.

Both groups are working on optimizing their experiments—stabilizing their lasers, further cooling the atoms within their traps, and improving their vacuum systems—in order to suppress atom loss and increase fidelity. In addition, the Wisconsin researchers have their sights on the multiqubit entanglement necessary for basic quantum computing. Says Saffman, "A primary goal for the next five years or so is running quantum programs on 10 to 20 qubits and studying error correction."

Johanna Miller

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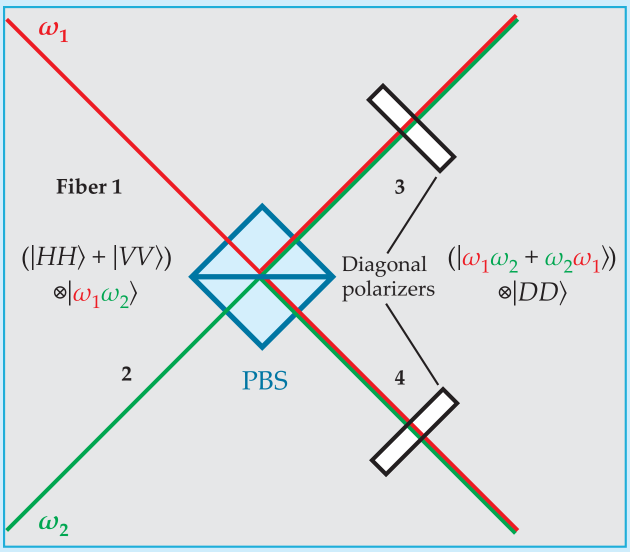
150-nm-diameter CNT. As shown in the images, Zewail and colleagues also monitored the temporal decay of the surface field by varying the delay times between the exciting laser pulse and the probing electron pulse, from zero (top) to 400 fs (bottom) and beyond. With tunable and temporally controlled light pulses, PINEM enables visualization of dynamical optical responses of various nanostructures. (B. Barwick, D. J. Flannigan, A. H. Zewail, *Nature* **462**, 902, 2009.) —SGB

From polarization entanglement to color entanglement. The strangeness of the quantum world is epitomized by entangled states, whose nonintuitive correlations cannot be mimicked by any classical system. These days experimenters routinely create two-photon states in which the photons' polarization is entangled. Now, starting with such a state, Sven Ramelow and Lothar Ratschbacher (Institute for Quantum Optics and Quantum Information and University of Vienna) and colleagues have entangled the frequencies of two photons. It's not the first demonstration of frequency entanglement, but earlier protocols relied on frequency filtering. In the Vienna work, only the two frequencies to be entangled are present in the initial state. The accompanying figure depicts the technique. Initially, the "red" photon in fiber 1 has a definite frequency, as does the "green" photon in fiber 2. The two photons have entangled polarizations—both are either horizontal or vertical. The key step is implemented by a polarizing beamsplitter that shunts the red photon into fiber 3 if it is horizontally polarized and into fiber 4 if it is vertically polarized. The PBS performs a similar operation on the green photon. The resulting intermediate state is passed through diagonal polarizers and, voila, the output has entangled frequencies. With a suitable initial state, report the Vienna researchers, their technique can transfer polarization entanglement onto any desired photon degree of freedom. (S. Ramelow et al., *Phys. Rev. Lett.* **103**, 253601, 2009.) —SKB



Synthetic magnetic fields. An ultracold gas of atoms known as a Bose–Einstein condensate (BEC) is a nearly ideal system for creating new states of matter or studying many-body quantum phenomena at macroscopic scales. (For one example, see the article on Anderson localization by Alain Aspect and Massimo Inguscio in Physics Today, August 2009, page 30.) The BEC's charge neutrality, though, hinders its use as a probe of phenomena that arise from Lorentz forces on electrons in a magnetic field; magnetic fields produce only Zeeman shifts. Researchers at the Joint Quantum Institute, a collaboration of NIST and the University of Maryland, have now removed that limitation. The researchers, led by Ian Spielman, began with a BEC of roughly 250 000 rubidium-87 atoms held at 100 nK. By illuminating the atoms with a suitable pair of laser beams close to resonance, they imprinted an effective vector potential **A*** on the system. In the presence of a detuning gradient, the vector potential depends on position in the trap. The spatial dependence can thus be engineered to give a nearly uniform synthetic magnetic field $\mathbf{B}^* = \nabla \times \mathbf{A}^*$ that *does* couple to neutral atoms. A signature of that field is the formation of vortices—the spots shown in this time-of-flight image of the BEC—that mark points about which the atoms swirl. Spielman and colleagues plan to add to their system a two-dimensional optical lattice, which may allow them to create, for example, exotic quantum Hall states of bosons. (Y.-J. Lin, R. L. Compton, K. Jiménez, J. M V. Porto, I. B. Spielman, *Nature* **462**, 628, 2009.) —RMW ■