

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.”

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References

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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 polariz-

ing 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 $\mathbf{A}^*$ 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

