Neutral atoms are entangled in hyperfine states via Rydberg blockade

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results of WIMP searches at the LEP and Tevatron colliders. In experiments like CDMS II, a few recoil energies can't specify the WIMP mass. But the fact that both CDMS II events had relatively low recoil energies, near 15 keV, suggests a mass somewhat lower than 60 GeV.

The only definite claim of WIMP-collision sightings to date was first announced in 2000 by the DAMA collaboration, whose sodium iodide detector sits in Italy's Gran Sasso underground laboratory.[3] DAMA's disputed results have for some years conflicted with the elastic-scattering upper limits reported by CDMS and the XENON10 collabora-

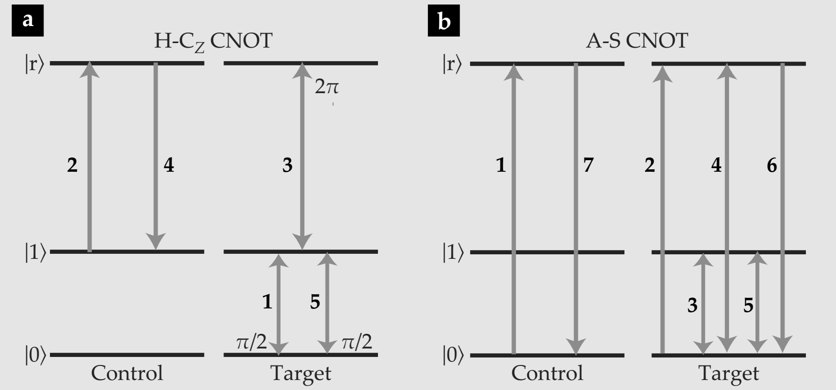

Figure 1. Two sequences of laser pulses that function as controlled-NOT, or CNOT, quantum gates by making use of Rydberg blockade. Both protocols flip the target atom's state when the control atom is in hyperfine state $|1\rangle$. The blue numbers indicate the order in which the pulses are applied, and all pulses are π pulses (of exactly the right duration to induce an excitation or de-excitation) except for those marked as 2π or $\pi/2$ pulses. **(a)** In the H-C_Z CNOT sequence, pulse 3 imparts a phase shift that changes the net effect of pulses 1 and 5. But if the control atom is excited to the Rydberg state $|r\rangle$, then pulse 3 is blocked. **(b)** In the A-S CNOT sequence, when the control atom is excited to $|r\rangle$, pulses 2, 4, and 6 are all blocked, so pulses 3 and 5 together leave the target atom state unchanged apart from a phase shift. But if the control atom is in state $|1\rangle$ and is not excited to $|r\rangle$, then pulses 2–6 have the net effect of swapping the target's hyperfine amplitudes. (Adapted from ref. 4.)

Again publishing their results back to back, both groups have now used Rydberg blockade to entangle pairs of atoms in two hyperfine levels of the atomic ground state. The Paris researchers did it by transforming their ground–Rydberg entangled state into a hyperfine–hyperfine entangled state.[3] The Wisconsin researchers constructed a quantum logic gate called a controlled-NOT, or CNOT, gate: a sequence of laser pulses, involving excitations to the Rydberg state, that changes the state of a target atom if and only if a control atom is in a particular hyperfine state.[4] Applying the CNOT gate when the control atom is in a superposition of states entangles the two atoms. A perfectly working CNOT gate, plus the ability to manipulate single qubits, can be the basis for all the qubit interactions that are needed in a quantum computer.

The Paris protocol

In their work last year, the Paris researchers blasted a pair of rubidium-87 atoms with a Rydberg-exciting laser pulse. Only one atom was excited, but the excitation was delocalized over the pair—that is, the pulse created a superposition of the two-atom states $|0r\rangle$ and $|r0\rangle$, where 0 is the ground state and r is the Rydberg state. Since such a superposition can't be represented as a product of two wavefunctions, one localized on each atom, it is an entangled state.

But the Rydberg states themselves aren't suitable for use as qubits. Rydberg atoms aren't confined by the optical traps, and they readily undergo spontaneous emission. More troubling, the entangled state was actually $(|r0\rangle + e^{i\phi}|0r\rangle)/\sqrt{2}$, where the phase ϕ depended on the positions of the atoms in their traps, which varied randomly from one repetition of the experiment to another. That uncontrollable variation hampered the researchers' efforts to verify that the atoms were really entangled and made it impossible to exploit the entanglement.

Now they've added a second laser pulse that moves the Rydberg atom into a different ground-state hyperfine level—call it $|1\rangle$. That pulse also imparts a phase to the system, but since it stimulates an emission rather than an absorption, and since the atoms don't move much in the 200 ns between the start of the first pulse and the end of the second, the two phases are nearly equal in magnitude and opposite in sign. To a good approximation, they create the symmetric superposition of $|01\rangle$ and $|10\rangle$.

The Madison method

The Wisconsin researchers considered two different pulse sequences for their CNOT gate. Figure 1 shows both, with the numbers indicating the order in which the pulses are applied. Most of the pulses are π pulses, which have exactly the right duration to move an atom from one state to the other. There is also a 2π pulse (which returns the atom to its initial state and imparts a π phase shift to it) and $\pi/2$ pulses (which can leave the atom in a superposition of states).

Figure 1a shows a CNOT sequence based on Hadamard (essentially $\pi/2$) pulses plus a controlled π rotation about the z axis, or H-C_Z CNOT. One can imagine it applied to control and target atoms that are both initially in state $|1\rangle$. The first pulse moves the target atom into a superposition of states $|1\rangle$ and $|0\rangle$. The second excites the control

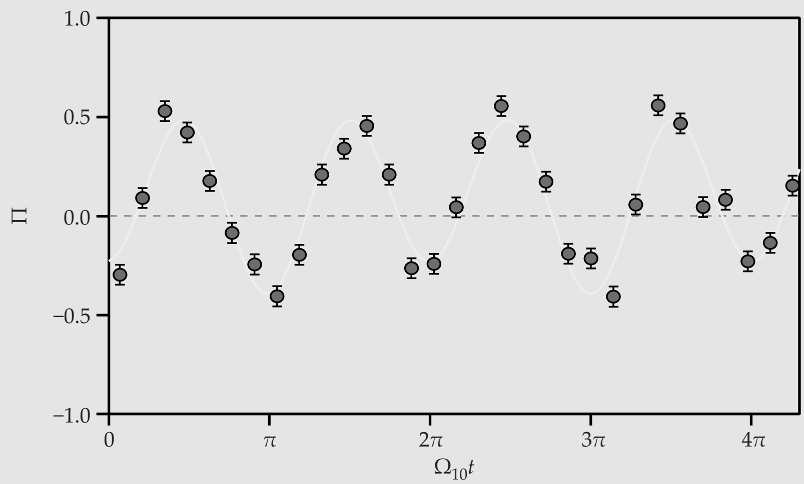

Figure 2. Entanglement can be verified by irradiating both atoms with a pulse of duration t and measuring the oscillation in the parity signal $\Pi = P_{00} + P_{11} - P_{10} - P_{01}$, where P_k is the probability of observing the system in state k. Here, the oscillation mainly occurs at twice the Rabi frequency, $2\Omega_{10}$, as expected for an entangled pair of atoms. The slight superposed oscillation at a frequency of Ω_{10} is due to iterations of the experiment in which one of the atoms was lost from its trap. (Adapted from ref. 3.)

When Jean-Dominique Cassini discovered Saturn's moon Iapetus in 1671, he was surprised to find it visible on just one side of its orbit around the planet. The moon's orbit had to be synchronous, he correctly inferred, with its leading hemisphere far darker than its trailing one. Some clever Earth-based IR radiometry 300 years later confirmed the extreme albedo difference, and images from the Voyager mission in the early 1980s revealed charcoal dark and frosty bright surfaces that interleave, like two halves of a tennis ball. But the origin of the pattern and sharpness of the dark–bright boundaries remained mysterious.

As early as 1974, Asoka Mendis and Ian Axford had proposed a plausible explanation: With its mean density close to that of water, Iapetus is a dirty ice ball. Dust from micrometeorites hitting the leading hemisphere, the pair theorized, might darken it enough to trigger the thermal migration of ice: sublimation from dark, warmer patches centered around the moon's equator and recondensation at bright, colder areas near the poles and on the trailing side. The brief proposal, overlooked by subsequent researchers, lay dormant for 33 years.

Data collected since 2004 by the *Cassini–Huygens* spacecraft offer the most compelling evidence yet for Mendis and Axford's view. In two companion papers, John Spencer of the Southwest Research Institute in Boulder, Colorado, Tilmann Denk of the Free University of Berlin, and their colleagues analyze *Cassini*'s visible and IR data of Iapetus's surface and present computer simulations that reproduce the observed albedo pattern and its likely 2.4-billion-year evolution from a modest initial dusting.[1,2]

Although shades of color are difficult to discern here, visible-spectrum images such as these photographs reveal a material coating Iapetus's leading side that is redder than the dirt presumed intrinsic to the moon there and on its trailing side. The foreign dust is thought to be swept up, like bugs on a windshield, as Iapetus orbits Saturn at 3.3 km/s. That idea gained additional support last year when the University of Virginia's Anne Verbiscer and colleagues, using the *Spitzer Space Telescope*, detected an enormous gossamer ring of particles tracking the retrograde orbit of Saturn's distant moon Phoebe.[3] Particles from the ring could spiral into Iapetus at 6.5 km/s, effectively sandblasting its leading side.

Iapetus's piebald appearance at low latitudes on the trailing side is clear evidence for the thermal segregation of ice from dirt. Thanks to the long exposure to the Sun during Iapetus's slow, 79-day axis rotation, the dark material reaches 129 K, warmer than any surface in the Saturn system except for internally heated fractures on Enceladus, while bright material remains a cooler 113 K. As micrometeorites impact the moon's surface, they "garden" it, churning up material to expose virgin ice crystals that can then sublime and recondense at cold traps elsewhere. Bright areas become brighter and dark areas become darker, probably to a thickness of tens of centimeters over a couple billion years, Spencer estimates.

The process happens both locally and globally. Ice can migrate from warm equator-facing crater walls to cool pole-facing ones, for example, or from one side of the moon to the other, giving rise to its two-faced appearance. Just 1500 km in diameter, Iapetus is small and lacks an atmosphere, which allows water molecules to follow ballistic trajectories up to hundreds of kilometers in range.

Still unresolved is the precise origin of the infalling dust. The dark surface components of Phoebe and Iapetus are both composed of coal-like hydrocarbons and are spectrally similar, but with an important distinction: Phoebe is gray—or, more precisely, neutral, with a flat spectrum in the visible and near-IR—not red. Planetary scientists are now puzzling over what might account for the difference.

Mark Wilson

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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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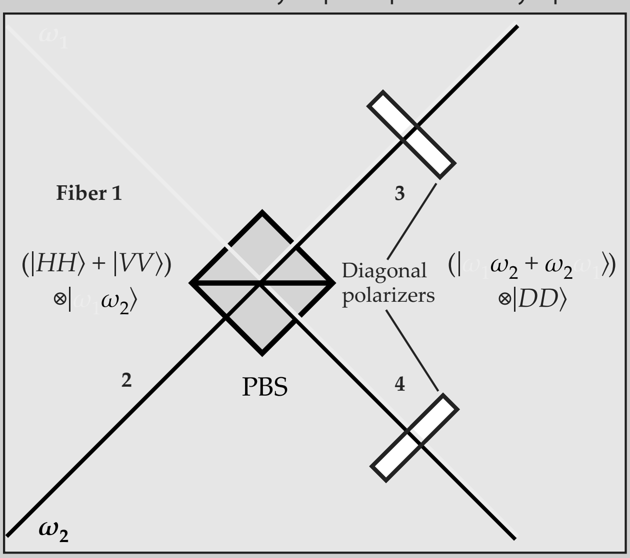
150-nm-diameter CNT. As shown in the images, Zewail and colleagues also monitored the temporal decay of the surface field by varying the delay times between the exciting laser pulse and the probing electron pulse, from zero (top) to 400 fs (bottom) and beyond. With tunable and temporally controlled light 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 ■