Experiments show blockading interaction of Rydberg atoms over long distances

The demonstration that one highly excited atom can inhibit the excitation of another far away holds promise for quantum computing with neutral atoms.

Ordinarily, two neutral atoms separated by much more than a few angstroms take no notice of each other. But when the valence electrons of two alkali atoms are excited to Rydberg states—states with very high principal quantum numbers n—the atoms can interact strongly at separations exceeding 10^4 Å (1 μm). When their nuclei are held a few microns apart, the strength of the interaction between two atoms raised to the same Rydberg state increases like n^{11}.

As reported in back-to-back papers appearing this month, two groups of experimenters have exploited that long-range interaction to demonstrate significant steps toward the goal of quantum computing with neutral atoms. A group led by Mark Saffman and Thad Walker at the University of Wisconsin–Madison reported the first observation of "blockade" interaction between a pair of Rydberg atoms.[1] (When the quantum state of one part of a system prevents or inhibits the excitation of another part, the latter's excitation is said to be blockaded.) And then a group at the Université Paris-Sud, led by Philippe Grangier and Antoine Browaeys, used Rydberg blockade to create an entangled quantum state between two neutral atoms.[2]

Although ions are easier to trap than neutral atoms, they present a special scaling problem when one thinks of assembling a large number of them in an array of separate traps for practical quantum computation. The strength and infinite range of the Coulomb force between ions make such an array susceptible to disruptive collective vibrational excitations. Neutral atoms in an optical lattice of traps avoid that problem (see PHYSICS TODAY, August 2007, page 21). The force between Rydberg atoms may have a remarkably long range. But, like a van der Waals force between molecules, it is much weaker than the Coulomb force and it falls off faster than $1/r^2$.

Blockade

Figure 1 illustrates the eventual use of Rydberg blockade envisioned by the Wisconsin experiment, with its two cold rubidium-87 atoms held in separate optical traps 10 μm apart. At so large a separation, one can easily address the atoms with separate lasers, and one can imagine blockade interaction even between non-nearest neighbors in an optical lattice.

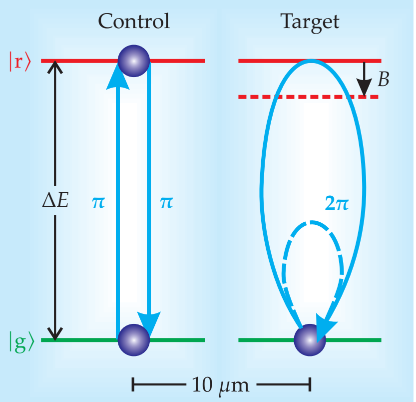

Figure 1. Rydberg blockade between two rubidium atoms 10 μm apart. A lone Rb atom's ground state $|g\rangle$ is separated from a particular highly excited Rydberg state $|r\rangle$ by an energy ΔE. If a pulse of the right duration (a π pulse) from a laser tuned to ΔE raises one atom (the control) from $|g\rangle$ to $|r\rangle$, the long-range interaction between Rydberg atoms shifts the target atom's $|r\rangle$ level by B, putting it out of resonance with a second laser also tuned to ΔE. So subjecting the target atom to a 2π pulse, which would take a lone atom on a round trip from $|g\rangle$ to $|r\rangle$ and back, fails when the nearby control atom is already in $|r\rangle$. (Adapted from ref. 1.)

Anticipating the use of such a pair of trapped atoms as a quantum-logic gate, the group labeled the two as the control atom and the target atom. For a lone Rb atom, the energy gap ΔE between the ground state $|g\rangle$ and an excited Rydberg state $|r\rangle$ with $n = 79$ is about 4 eV. When the atom is being irradiated with an optical laser beam whose wavelength is precisely tuned to ΔE, its wavefunction oscillates coherently between $|g\rangle$ and $|r\rangle$ at a microwave frequency (the so-called Rabi frequency) that depends on the radiation's intensity. The Rabi frequency ν_R is a direct measure of the strength of the coupling between the atom and the laser beam. At any given moment in the Rabi oscillation, the valence electron is in a linear superposition of the $|g\rangle$ and $|r\rangle$ states. And one can put the atom at will into either of those two eigenstates by controlling the duration of the excitation laser pulse.

The presence of the control atom 10 μm away does nothing to inhibit the Rabi oscillation of the target atom—so long as the control remains in the ground state. But if one first raises the control to $|r\rangle$, the Rydberg energy gap confronting the target atom is lowered from ΔE by a tiny shift B due to the attractive long-range interaction between two Rydberg atoms. Although the blockade shift B is only of order 10^{-8} eV, it is enough to put the target atom's $n = 79$ state out of resonance with the excitation laser—without bringing a neighboring Rydberg state into resonance. To the extent that ν_B, the frequency B/h corresponding to the blockade shift, significantly exceeds ν_R, the excited control atom blocks the excitation of the target atom.

Thus one has, in principle, the makings of a "controlled not" quantum logic gate. In a classical CNOT gate, the binary state of the control bit determines whether or not the target bit's state will be flipped. The potential power of quantum computing comes from the possibility that each bit, called a qubit, can be in a coherent superposition of its binary states.

In the Wisconsin experiment, separate excitation laser beams, both tuned to ΔE, were focused on each of the two trapped atoms. If the control atom is left unexcited and the target atom in its ground state is subjected to an excitation pulse whose duration is precisely $1/\nu_R$ (a so-called 2π pulse), the target atom makes a round trip to $|r\rangle$ and back to $|g\rangle$. In the process, its ground-state wavefunction acquires a phase shift of π. But if one first excites the control atom with a pulse of half that duration (a π pulse), which elevates it to $|r\rangle$, the

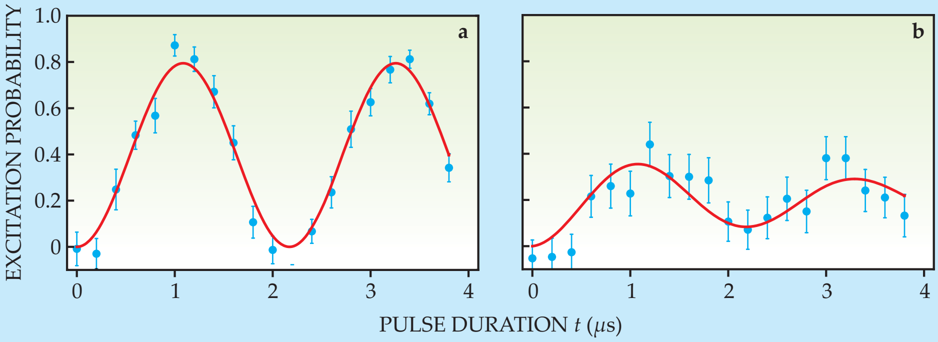

Figure 2. The amplitude of the Rabi oscillation of the target atom between its ground state |g⟩ and the $n = 79$ Rydberg state |r⟩ during irradiation with laser light tuned to ΔE depends on the state of the control atom 10 μm away. **(a)** When the control in the Wisconsin experiment,[1] is held in |g⟩, the oscillating probability that the target will be found in |r⟩ after an irradiation pulse of duration t peaks at about 80%. **(b)** When the control is held in |r⟩, Rydberg blockade reduces the peak probability to about 30%. The fitted theoretical curves take account of experimental limitations such as the deterioration of coherence with increasing t. (Adapted from ref. 1.)

resulting blockade shift prevents the subsequent 2π pulse from taking the target atom through |r⟩. So its ground state acquires no phase shift.

As befits a CNOT gate, the target atom's phase shift depends on the binary state of the control atom. But for a useful quantum logic gate, one has to render the phase-shift information observable and preserve it in memory. To that end, there's a standard trick for translating a π phase shift into a flip of the atom's hyperfine ground state (see Physics Today, March 1996, page 21). "We're working on that," says Saffman, "but we haven't done it yet."

What Saffman and company have done is measure the effect of the control atom's state on the Rabi oscillation of the target atom 10 μm away (see figure 2). The experimental sequence, repeated thousands of times, begins with loading a single cold ^{87}Rb atom into each of the two adjacent optical traps. In half the runs (figure 2a), the control atom is left unexcited in its ground state while the target atom is irradiated by its excitation beam with a pulse of variable duration t.

If the target atom emerges from the excitation pulse in the excited Rydberg state, it will promptly be ionized by the trapping light (which was turned off during the pulse) and flee the trap. Turning the trapping light back on provides a measurement of the target atom's quantum state at the end of the excitation pulse. So the probability that the atom was in |r⟩ and therefore left the trap, plotted in the figure as a function of t, traces out the Rabi oscillation between the pure |g⟩ and |r⟩ states. The observed oscillation period of about 2 μs agrees well with what the group predicts from the intensity of the laser excitation. And the observation that the peak excitation probability doesn't get much above 80% is understood by the Wisconsin group in terms of experimental imperfections.

By contrast, figure 2b shows what happened to the target atom's Rabi oscillation when the control atom was in |r⟩, having been raised to the Rydberg state by a π pulse from its own excitation beam. Instead of 80%, the peak probability of finding the target atom in |r⟩ was now only about 30%.

That blockade-violating amplitude for both atoms to be excited is, in fact, three times as high as one would expect in the absence of experimental limitations. In an ideal experiment, the probability P_2 that both atoms are in |r⟩ is given by

$$P_2 = \nu_R^2/(\nu_R^2 + 2\nu_B^2),$$

which comes to only about 10%, given that ν_B was about twice ν_R. But based on its Monte Carlo simulations, the group attributes the observed blockade efficiency $(1 - P_2)$ of only 70% largely to imperfect preparation and detection of quantum states.

For a practical quantum logic gate, one would of course want the blockade efficiency to approach 100%. Toward that end, the Wisconsin group repeated the blockade demonstration with the atoms raised to the $n = 90$ Rydberg state. For that state, B is three times what it is at $n = 79$, and the blockade efficiency should, with perfect state preparation and detection, exceed 98%. In the actual experiment it turned out to be about 90%. "We're hoping eventually to get up to $n = 150$," says Saffman.

Because the Rydberg interaction is potentially so strong even at a separation of 10 μm, one could hope to operate a Rydberg blockade gate at high Rabi frequency, which would make for very fast logic operations.

Entangled in Paris

In a real quantum computing task, the input control qubit would, in general, be in a coherent superposition of |g⟩ and |r⟩, which would determine the coherent superposition state of the target atom's output qubit. So an essential attribute of a quantum logic gate must be the quantum entanglement of its control and target entities. Two quantum entities are said to be entangled if their joint state cannot be expressed as a product of their individual wavefunctions. And quantum entanglement implies a degree of correlation that no classical system can mimic.

The Paris group's experimental setup was similar to that of the Wisconsin group. But to find evidence of the requisite entanglement, Grangier and company did not address the two Rb atoms with separate laser beams. Instead they directed the same excitation pulse simultaneously at both atoms, which were held in optical traps only 3.6 μm apart. That smaller separation does less to show off the extraordinary range of the Rydberg interaction, but it facilitates the demonstration of entanglement.

For a given Rydberg state, the long-range interaction strength decreases with the separation r something like $1/r^3$. Grangier and company chose to excite the Rb atoms to the $n = 58$ Rydberg state, for which the unusually strong blockade shift B is about 10 times greater at a separation of 3.6 μm than it is for $n = 90$ at 10 μm.

With both atoms in the electronic ground state, one can denote their joint wavefunction as |g,g⟩, taking the first argument to refer, say, to the atom closer to the laboratory's door. Irradiating that state with the laser's wavelength tuned to ΔE for $n = 58$ can yield either |g,r⟩ or |r,g⟩ but never—to the extent that the Rydberg blockade is effective—|r,r⟩. And indeed that's what the Paris group found, with a blockade efficiency of about 90%.

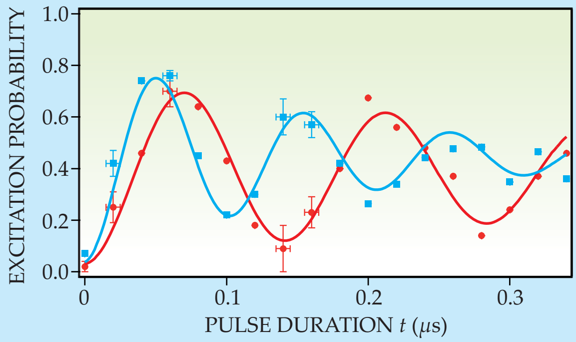

Figure 3. Quantum entanglement by Rydberg blockade interaction of two rubidium atoms trapped 3.6 μm apart in the Paris experiment[2] is demonstrated by the observation that the Rabi oscillation of the two-atom system (blue data points and fit) has a frequency greater by a factor of 1.38 ± 0.03 than that of a lone atom (red) irradiated by the same laser beam. That's close to the predicted factor of $\sqrt{2}$. A single laser pulse simultaneously irradiates both trapping sites for a time t. When both traps were filled at the start of irradiation with atoms in the ground state, the data trace the probability that one (but not both) was in the excited Rydberg state at the end of the pulse. Gradual loss of quantum coherence contributes to the observed decrease of the oscillation amplitude over time. (Adapted from ref. 2.)

"Only one of the two atoms gets excited," says Grangier, "but the excitation is delocalized over both atoms. And that's how they become entangled in our experiment." The resulting quantum state is presumed to have the entangled form

$$|\Psi\rangle = (|r,g\rangle + e^{i\phi}\,|g,r\rangle)/\sqrt{2}\,,$$

where the phase difference ϕ comes simply from the different positions of the two atoms in the beam of the excitation laser.

That entangled wavefunction implies that the system oscillates between $|g,g\rangle$ and $|\Psi\rangle$ with a frequency $\sqrt{2}\,\nu_R$, where ν_R would be the Rabi oscillation frequency of a lone Rb atom in the same laser beam. So even though only one atom at a time can be in the excited state $|r\rangle$, the excitation rate is predicted to be enhanced by the entangled presence of the second atom. And that is indeed what Grangier and company found. Figure 3 compares the observed Rabi oscillation when one of the two traps is left empty with what happens when Rb atoms are loaded into both traps. In the latter case, the Rabi oscillation is clearly faster. And the measured ratio of oscillation frequencies, 1.38 ± 0.03, is consistent with the predicted $\sqrt{2}$.

A rigorous "proof" of entanglement would require demonstrating a violation of Bell's inequality, the upper limit of correlation between separated parts of a classical system. "But," says the University of Connecticut's Phillip Gould, "it's hard to explain the observed $\sqrt{2}$ speedup by anything short of actual entanglement."

The Paris group is confident that for practical quantum gates, the entanglement of the two atoms can survive the transfer of the electronic-excitation information to long-lived hyperfine qubits. As a byproduct, that transfer would also serve to cancel out the dependence of the entangled state on the phase difference ϕ. The ϕ dependence would otherwise contribute to decoherence because the thermal motion of the atoms trapped at μK temperatures causes their positions and therefore ϕ to vary from one pulse to the next.

"Rydberg blockade is particularly well adapted for quantum information processing," says Grangier, "because it provides a scheme for deterministic—as distinguished from probabilistic—creation of entangled hyperfine states." That is, one can essentially create an entangled state at will. Probabilistic schemes, by contrast, require multiple tries and some sort of signal to announce the creation of an entangled state.

An experiment by the University of Maryland's Chris Monroe and coworkers gives an extreme but provocative example of the probabilistic creation of entangled hyperfine states between a pair of ions held a meter apart (see Physics Today, November 2007, page 16). The ions were much too far apart to interact, but the experimenters did mix the decay photons from their simultaneous but separate excitations. And a few times per billion tries, the photon mixing revealed that the ions had become entangled without ever having met.

Bertram Schwarzschild

References

1. E. Urban et al., *Nat. Phys.*, doi:10.1038/nphys1178 (in press).
2. A. Gaëtan et al., *Nat. Phys.*, doi:10.1038/nphys1183 (in press).