

Physics Nobel honors pioneers in quantum optics

David Wineland used light to manipulate trapped atoms, and Serge Haroche used atoms to manipulate trapped light.

The aspiring quantum experimentalist faces a conundrum. One can't well experiment on a quantum system without interacting with it—how else to impose initial conditions and measure outcomes? But interactions with the environment cause a quantum system to decohere and lose its quantum nature. Fifty years ago, the temptation might have been to concede that many of the weird phenomena predicted by quantum mechanics—entanglement and nonlocality, for instance—would be forever consigned to the realm of thought experiments. In recent decades, however, bolstered by technologies such as atom and ion traps, tunable lasers, and photon-trapping cavities, researchers have been increasingly successful at navigating the experimental stumbling blocks of quantum mechanics.

Helping to lead the way have been David Wineland (NIST, Boulder, Colorado), who devised techniques to control the quantum states of single atoms, and Serge Haroche (Collège de France and École Normale Supérieure, Paris), who achieved similar command over photons. Citing the researchers' respective methods for manipulating quantum systems "in ways that were previously thought unattainable," the Royal Swedish Academy of Sciences awarded Wineland and Haroche equal shares of the 2012 Nobel Prize in Physics.

Cold, trapped ions

Wineland has built a career out of making increasingly precise spectroscopic measurements of atoms. Such measurements call for a particular skill set: the abilities to manipulate and measure an atom's internal electronic states and to hold the atom relatively still. Pulsed radiation techniques—including those developed by Wineland's graduate thesis adviser, Norman Ramsey—provide the necessary control over an atom's internal states. And as early as the 1950s, Wolfgang Paul and Hans Dehmelt had demonstrated how strategic assemblages of electrodes could be used to construct atom- and ion-trapping electromagnetic potentials. Dehmelt, Wineland's postdoctoral adviser at the University of Washington during the early 1970s, once held a lone electron in such a trap for nearly a year.

One problem in spectroscopy, however, is that an atom tends to oscillate harmonically within a trap, and the resulting Doppler shifts broaden the atom's spectral lines. During Wineland's postdoc, he and Dehmelt conceived a technique, now known as sideband cooling, to damp those oscillations. (See the article by Wineland and Wayne Itano, *PHYSICS TODAY*, June 1987, page 34.)

The main idea was to red detune a laser from the energy $h\nu$ of an atomic transition by an amount equal to a quantum of the vibrational motion of the atom in the trap. That way, if the atom lies in the electronic ground state and has N vibrational quanta, a photon absorption will kick it up to an excited electronic state with $N - 1$ vibrational quanta. Most likely, the atom will spontaneously emit a photon of energy $h\nu$, leaving it back in the electronic ground state but with one less vibrational quantum. With repeated excitations and emissions, the ion can be cooled to a near standstill. (Unknown to Wineland and Dehmelt, Stanford University's Arthur Schawlow and Theodor Hänsch were simultaneously devising a nearly identical cooling strategy.)

Sideband cooling's laboratory debut had to wait until 1978, by which time Wineland had left Seattle for a staff position at NIST (then the National Bureau of Standards). That year Dehmelt, working with Peter Toschek in Heidelberg, Germany, demonstrated cooling of a cloud of barium ions, and a team led by Wineland independently demonstrated

the technique on magnesium ions.¹ The success meant they could all but eliminate Doppler broadening of spectral lines, and within a few years, James Bergquist, Wineland, and coworkers had measured a mercury ion transition to a resolution of better than one part per trillion. (See *PHYSICS TODAY*, September 1989, page 17.) But the ability to cool an ion to the vibrational ground state also confers the ability to reintroduce vibrational quanta in a controlled manner. And with that, the stage was set for spectacular tests of quantum mechanics.

Cavity QED

In the mid 1960s, while Wineland was still a PhD student at Harvard, Serge Haroche enrolled in his first physics courses at École Normale Supérieure (ENS). One, a quantum mechanics course, was taught by Claude Cohen-Tannoudji. "When I started at the École Normale," Haroche recalls, "all I knew was that I wanted to do physics. It was only because I was fascinated by [Cohen-Tannoudji's] lectures that I got drawn in to quantum optics."

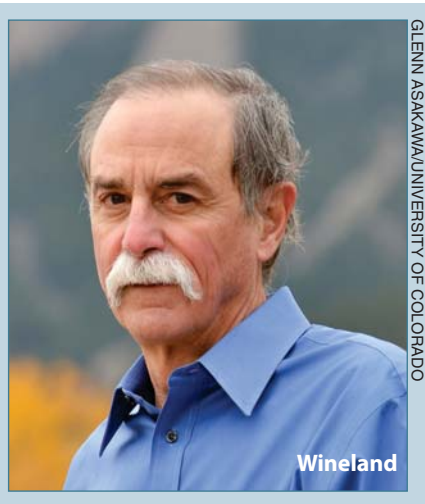
So intrigued was Haroche that he chose Cohen-Tannoudji as his thesis adviser, and together they developed the dressed-atom formalism, a mathematical technique for expressing electromagnetic field effects on atoms in terms of photons. Later, as a young professor at the University of Paris VI and ENS, Haroche turned his attention to Rydberg atoms, highly excited atoms whose unusual physical properties had recently begun to interest atomic physicists.

Because orbital radius scales as the



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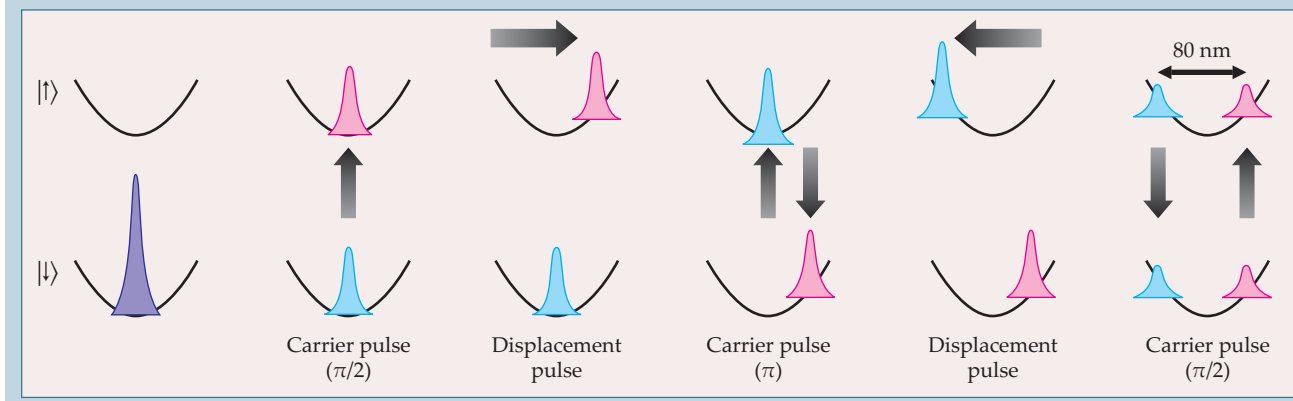
Haroche



GLENN ASAKAWA/UNIVERSITY OF COLORADO

Wineland

Figure 1. A laser-cooled ion trapped in a harmonic potential well can be placed in two locations at once by entangling its vibrational and hyperfine states. A $\pi/2$ carrier pulse prepares the ion's wavefunction in a superposition of the $|\downarrow\rangle$ and $|\uparrow\rangle$ hyperfine states, and a polarized displacement pulse selectively excites the $|\uparrow\rangle$ wavepacket into oscillatory motion. A π carrier pulse then flips the wavepackets' hyperfine states so that the next displacement pulse sets the second packet in motion. To detect the superposition, each packet must first be prepared, with a final carrier pulse, into a superposition of hyperfine states. When the wavepackets oscillate perfectly out of phase, the interpacket spacing can exceed 80 nm. (Adapted from ref. 1.)



square of the principal quantum number n , a Rydberg atom with $n \approx 50$ can span nearly 100 nm, thousands of times larger than in the ground state. In the late 1970s and 1980s, a handful of atomic physicists—including Daniel Kleppner of MIT, Herbert Walther of the Max Planck Institute of Quantum Optics, and Haroche—began to recognize that the large orbits make Rydberg atoms extremely sensitive to microwave radiation and, as such, ideal test subjects for an experimental field that would come to be known as cavity quantum electrodynamics.

Cavity QED is, in essence, the study of how atoms and electromagnetic fields interact in confined space. Just as placing a particle in a potential well restricts its energy to certain quantized values, placing an atom in a reflective cavity restricts the kind of photons it can absorb and emit. For instance, an excited atom confined to a cavity will spontaneously emit only if the transition frequency corresponds to a cavity mode; and then it does so more readily than it would in free space. (See Haroche and Kleppner's article in *PHYSICS TODAY*, January 1989, page 24.) Rydberg atoms, prone to couple with light, provided a best chance for glimpsing those and other cavity effects in the lab.

In the ensuing friendly race to develop experimental cavity QED, Kleppner got off to a fast start. By firing Rydberg atoms through a cavity consisting of narrowly spaced aluminum plates, his group showed that confinement could indeed suppress spontaneous emission.

A cavity's quality can be expressed in terms of its Q factor—the average number of round trips a photon makes be-

fore escaping to the environment—and Kleppner's had a Q factor of order 10^3 . Walther's group, by contrast, achieved Q factors near 10^9 by using a closed niobium cavity that became superconducting when chilled to a few kelvin; atoms entered and exited the cylindrical cavity through tiny holes. The cavity could store a photon for more than 100 ms, long enough for it to travel the equivalent of Earth's circumference. That high-quality cavity allowed the team to create a maser with a beam of atoms so dilute that only one atom occupied the cavity at a time.

"Some of the other groups were so far ahead," recalls Kleppner of the early days of Rydberg-atom experimentation, "that I was a little concerned that Serge might not be able to catch up. Well, that concern didn't last long."

Haroche ultimately found success by arranging superconducting niobium mirrors as a Fabry-Perot cavity, with the concave mirrors spaced a few centimeters apart. The open design sacrificed some of the cavity's quality but allowed Rydberg atoms to be prepared in delicate superpositions that would have been destroyed in a closed cavity. And having devised a way to fire atoms through the gap at predetermined speeds, Haroche and company could precisely control the duration of each atom-cavity interaction.

Chasing Schrödinger's cat

Wineland's and Haroche's respective masteries of light-matter interactions were showcased to stunning effect in a pair of 1996 experiments reminiscent of the famous Schrödinger's cat thought experiment: Each researcher pulled off the quantum mechanical "parlor trick"

of using entanglement to create a coherent superposition of what would normally be regarded as classical states.

At NIST, Christopher Monroe, Wineland, and coworkers placed a single trapped beryllium ion in two distinct locations, nearly a tenth of a micrometer apart, at once.² As depicted in figure 1, they first cooled the ion to its motional ground state $|0\rangle$ and prepared it in the $|\downarrow\rangle$ hyperfine level of the electronic ground state. A so-called $\pi/2$ carrier pulse, tuned to the hyperfine splitting, drove the ion into a superposition of the $|\downarrow\rangle$ and $|\uparrow\rangle$ hyperfine levels. A displacement pulse, polarized so as to selectively address the $|\uparrow\rangle$ state, then kicked that part of the superposition into an oscillating state $|\alpha\rangle$. In the resulting entangled state, $|\downarrow\rangle|0\rangle + |\uparrow\rangle|\alpha\rangle$, one wavepacket oscillated in the trap while the other remained nearly still.

Next, a π carrier pulse flipped each packet's hyperfine state so that the next displacement pulse kicked the second wavepacket into an oscillating state $|\alpha'\rangle$. At that point, the ion, described by the wavefunction $|\uparrow\rangle|\alpha'\rangle + |\downarrow\rangle|\alpha\rangle$, consisted of two wavepackets oscillating with a relative phase determined by the phases of the two displacement pulses. When the oscillations were perfectly out of phase, the inter-wavepacket spacing exceeded 80 nm—10 times the size of the wavepackets themselves.

A final $\pi/2$ carrier pulse prepared each wavepacket in a hyperfine superposition, so that the two oscillating states produced a phase-dependent interference. That interference, detectable via fluorescence techniques, served as evidence of the coherent nature of the oscillating-state superposition.

At ENS, Haroche, Jean-Michel Raimond, Michel Brune, and coworkers performed the analogous feat of creating an electromagnetic field that points in two directions at once.³ As illustrated in figure 2, the team fired Rydberg atoms one by one through a superconducting microwave cavity in which a coherent field consisting of a few photons had been trapped. Just before the atom entered the cavity, a $\pi/2$ microwave pulse prepared it in a superposition of the energy levels $n = 51$ ($|+\rangle$) and $n = 50$ ($|-\rangle$). The cavity resonance was slightly detuned from the atomic transition frequency, so the atom couldn't absorb or emit a photon. It could, however, shift the trapped field's phase by subtly altering the refractive index in the cavity. The phase shift φ depends on the Rydberg state, $|+\rangle$ or $|-\rangle$, so the resulting entangled state could be expressed as $|+\rangle|\varphi_+\rangle + |-\rangle|\varphi_-\rangle$.

To detect the cavity field's superposition, the researchers mixed the Rydberg states of the exiting atom with a second $\pi/2$ pulse and then repeated the entire sequence with a second Rydberg atom. That created an atom-cavity-atom entanglement in which the two atoms were indistinguishable. Therefore, when the final Rydberg states were measured with a field-ionization detector, the atoms interfered in a way that betrayed the coherent nature of their superposition—and the cavity's. Moreover, just as decoherence theory predicts, Haroche's team saw the interference diminish with increasing time delay between the two atoms' passages, as cavity photons leaked into the environment. (See Haroche's article in *PHYSICS TODAY*, July 1998, page 36.)

The quantum information era

A two-level quantum system—such as the hyperfine levels used in the NIST experiment or the Rydberg levels used at ENS—can serve as a quantum bit, or qubit. Like a classical bit, a qubit can occupy a 0 or 1 state, but, unlike a classical bit, it can also exist in a superposition of both states at once. So in theory, a quantum computer comprising N qubits can occupy 2^N states and solve some problems exponentially faster than could a classical computer. (See the article by Ignacio Cirac and Peter Zoller, *PHYSICS TODAY*, March 2004, page 38.)

Until the 1990s, the idea of quantum information was entirely speculative, but the promise of realizing a quantum computer was bolstered when a NIST team headed by Wineland and Monroe managed to construct a deterministic

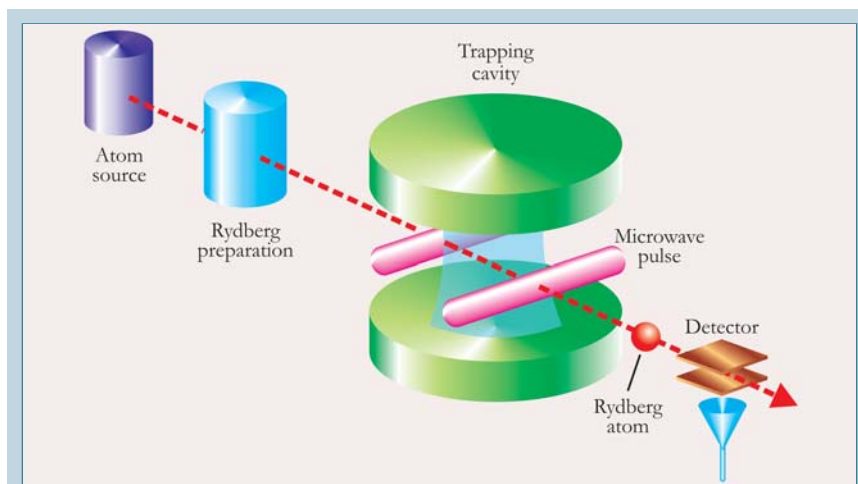


Figure 2. A quantum superposition of electromagnetic fields can be created by entangling atoms with trapped light. A first atom is prepared in a highly excited Rydberg state. Before it enters the trapping cavity, a microwave pulse places it in a superposition of two Rydberg states, each of which imparts a unique phase shift on the harmonically oscillating cavity field. After the atom exits the trapping cavity, its Rydberg states are mixed by a second microwave pulse, and the entire sequence is repeated with a second atom. The cavity-field superposition is evidenced by atom-atom interference, observable as correlations in the two atoms' detected Rydberg states. (Adapted from ref. 2.)

quantum logic gate between hyperfine and harmonic-oscillator qubits in a trapped ion. (See *PHYSICS TODAY*, March 1996, page 23.) Soon, other groups followed suit with variations on quantum logic, and today a handful of labs regularly experiment with tiny quantum computers consisting of a few logic gates. Still, the powerful computational devices envisioned by the field's founders remain to be realized.

Quantum control over atoms and photons has proved useful in other ways. By exploiting entanglement between Rydberg atoms and microwave cavity fields, Haroche and coworkers managed the delicate feat of detecting the presence or absence of a photon in a cavity without destroying the photon. (See *PHYSICS TODAY*, October 1999, page 22.) They've also observed quantum jumps of a cavity's photon number, again without sapping the cavity of photons. (See *PHYSICS TODAY*, June 2007, page 21.) In that work, there's yet another parallel with Wineland: In 1986, the NIST group was among the first—along with Dehmelt's and Toschek's groups—to observe quantum jumps of a trapped atom.

Wineland and his colleagues have also exploited simple quantum logic gates in their continuing quest to build a better clock. Their gated-ion clocks are now accurate enough to detect the tiny general relativistic effects of a change in elevation of a mere foot or so. (See *PHYSICS TODAY*, November 2010, page 16.)

Wineland and Haroche show few signs of slowing down. "For 30 or 40 years," as Gerhard Rempe (Max Planck Institute of Quantum Optics) puts it, "it has been one experiment after the other—each one more spectacular than the one before."

The laureates

David Wineland, born in 1944 in Wauwatosa, Wisconsin, earned a bachelor's degree in physics from the University of California, Berkeley. After completing his PhD and postdoctoral studies, he joined the time and frequency division at NIST, where he remains today. He also is affiliated with the University of Colorado Boulder.

Serge Haroche was born in 1944 in Casablanca, in what was then the French protectorate of Morocco. He settled in France with his family in 1956, then studied at ENS and earned a PhD in physics from the University of Paris VI. Since completing postdoctoral studies with Stanford's Schawlow, Haroche has taught at the University of Paris VI, École Polytechnique, Harvard, Yale University, and ENS. He holds the chair of quantum physics at the Collège de France and serves as the institution's director.

Ashley G. Smart

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