# Atom interferometer detects the birth and death of single photons without destroying them

**Since the 1980s physicists have used photons to track quantum jumps in single atoms. Now they can use atoms to track quantum jumps of light.**

**Imagine trapping** less than half a photon's worth of energy between two perfect mirrors. Most of the time, the electromagnetic field will be in its zero-photon ground state. But every now and again, the EM field will jump to its one-photon excited state, linger, then jump back down.

Recording a string of such jumps lies at the single-photon limit of quantum electrodynamics. To reach it, an experimenter needs not only to perform a delicate quantum nondemolition (QND) measurement, but also to sustain the feeble field for long enough to see at least one up-and-down jump. Both feats are hard to pull off; combining them is even harder.

A team from the École Normale Supérieure (ENS) in Paris has done just that.[1] Michel Brune, Serge Haroche, Jean-Michel Raimond, and their students sent a stream of specially prepared rubidium atoms through an optical cavity that contained on average 0.06 microwave photons. The atoms, thanks to their extreme sensitivity to electric field, picked up a measurable signal that depended on, but didn't change, the number of photons present. An atom interferometer read out the signal, which included unmistakable quantum jumps.

The ENS researchers had done similar QND measurements before. In 1999 they detected the presence of a single trapped photon (see PHYSICS TODAY, October 1999, page 22). In that experiment each photon stayed in the cavity just long enough—1 ms—for the atoms to sense its presence before it leaked away. To see jumps, the ENS researchers had to extend the trapped photon's lifetime to several seconds. Making the necessary improvements to the cavity took eight years.

## Circular Rydberg

It's the atoms that made improving the cavity so hard. To sense the state of a few-photon microwave field, the ENS team uses rubidium atoms, whose outer electrons are excited from their $n = 5$ ground state to the $n = 50$ Rydberg state. In such a far-flung orbital, an outer electron barely feels the Coulomb potential of the nucleus. The few-meV energy of a microwave photon suffices to promote an electron to the $n = 51$ state.

Ordinarily, such high Rydberg states are too ephemeral to serve as practical probes. However, the circular Rydberg states, those whose orbital momentum and magnetic quantum numbers are maximal, last longer. The ENS team, along with Nicim Zagury, first proposed using them for QND measurements in 1990.[2]

Unfortunately, the states' sensitivity to electric fields, so helpful in QND detection, also makes the atoms vulnerable to weak, stray fields that emanate from the apparatus. To mitigate the fields' unwanted influence, the opening through which the atoms enter and exit the cavity must be wide. But the more open a cavity, the closer to perfection its mirrors must be to retain the field. If a photon meets the slightest deviation in figure or roughness in surface, it will quickly escape.

For their 1999 experiment, the ENS researchers trapped a standing microwave between concave mirrors of solid niobium. Niobium's superconductivity accounts for the somewhat exotic choice of material. At 9.3 K, niobium's $T_c$ is the highest of all the elemental superconductors. At the cavity's operating temperature of 0.8 K, niobium reflects microwave radiation with near perfection.

One way to characterize a cavity's leakiness is with the $Q$ factor. ($Q = \omega E/P$, where $\omega$ is the resonant frequency, $E$ the stored energy, and $P$ the power dissipated.) To trap a photon long enough to see a jump, the ENS team calculated it needed to boost the $Q$ factor of its niobium mirrors 100-fold to $10^9$. And that's where the challenge lay. Niobium is difficult to machine to high precision.

Fortunately for the ENS team, quantum opticians aren't the only physicists who use superconducting niobium mirrors. Pierre Bosland, Eric Jacques, and Bernard Visentin of France's Atomic Energy Commission (CEA) develop high-$Q$ mirrors for particle accelerators. Instead of grinding down blocks of solid niobium, they make mirrors out of softer, easier-to-machine copper and then sputter a thin layer of niobium on top.

With CEA help, ENS researcher Stefan Kuhr, who's now at Johannes Gutenburg University in Mainz, Germany, and graduate student Sébastien Gleyzes made a pair of niobium mirrors (see cover). Their $Q$ factor is $5.6 \times 10^9$.

## Ramsey interferometer

Figure 1 depicts the ENS experiment, which begins when atoms leave their source, an oven, at a speed of about 300 m/s. They take about 1 ms to cross the apparatus, with about 2 ms delay between atoms.

Precisely tuned laser light (green in the figure, blue and infrared in reality) excites rubidium atoms to the $n = 50$ circular Rydberg state, which the ENS team labels $g$. Next, the atoms pass through a microwave cavity—the first stage of a so-called Ramsey interferometer—which puts the atoms in an equal superposition of $g$ and the $n = 51$ circular Rydberg state, which the ENS team labels $e$.

Once through the first Ramsey cavity, the atoms pass between the two niobium mirrors that form the trapping cavity. The mirrors' shape, separation, and operating temperature allow a nine-node standing wave to occupy the cavity. By means of a piezoelectric actuator, the wave's frequency is tuned away from the $g \to e$ transition, which occurs at around 51 GHz.

Detuning is crucial to the experiment. If there's a photon in the cavity, its electric field imposes an additional phase on the $e$ and $g$ states as the atoms pass through. Although the cavity field is far enough from the $g \to e$ transition that the atoms barely absorb energy, it's still close enough that the phases acquired by the $e$ and $g$ states are significantly different.

Once through the second Ramsey cavity, the atoms enter the detector, whose electric field of 100 V/m ionizes the loosely bound Rydberg atoms. Almost every atom is recorded by the detector, which can also distinguish the $e$ and $g$ states.

The second Ramsey cavity is tuned to rotate an equal superposition of $e$ and $g$ back to $g$. That restoration happens when the cavity is empty. When the cavity contains one photon, the degree of detuning changes the relative phases

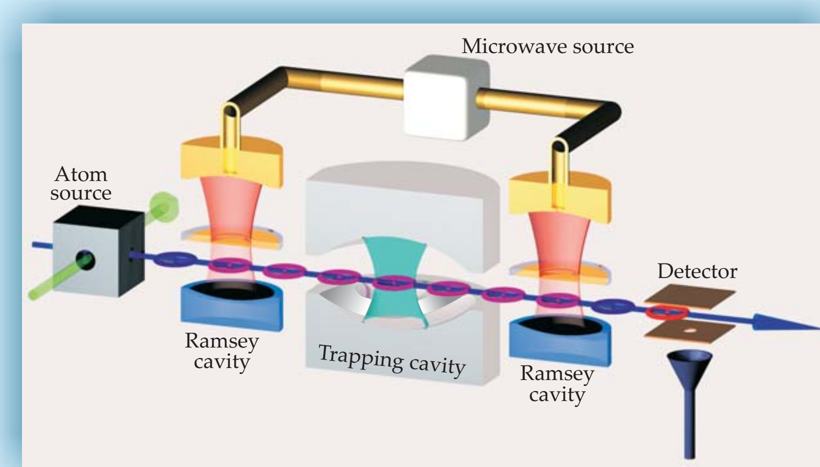


**Figure 1. Quantum jumps** between the zero- and one-photon states of a trapped field can be followed without destroying the field. The key lies in using atoms prepared in circular Rydberg states. After passing through the two Ramsey cavities and the trapped field, the atoms end up at the detector in one of two states depending on the presence of a trapped photon. (Adapted from ref. 1.)

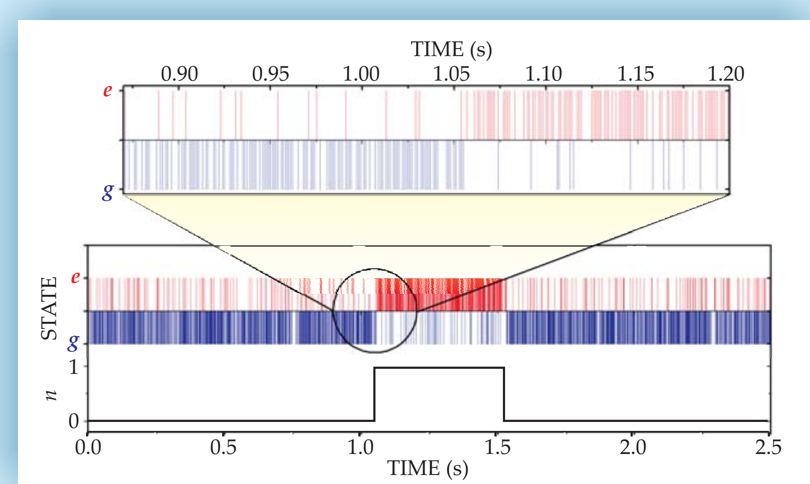


**Figure 2. The state of a trapped microwave field** was recorded by more than 2000 individual atoms after they flew through the cavity. Each colored bar represents a single detected atom: red (excited) for one photon, blue (ground) for no photon. Because of imperfections, the correspondence between the atom's state and the photon's presence isn't exact. Still, an upward quantum jump clearly occurred after 1 s followed by a downward jump 0.5 s later. (Adapted from ref. 1.)

of *e* and *g* and therefore the proportion of atoms detected on those states. Setting the detuning at just the right value ensures that the second Ramsey cavity will rotate the superposition to *e* whenever a photon is present. Thus, detecting an atom in *g* means no photon; detecting an atom in *e* means one photon.

Figure 2 shows the result of an experimental run that lasted 2.5 s. Each vertical bar corresponds to the detection of one of the 2000 or so atoms sent through the cavity. Most of the time, barring noise, the atoms revealed an empty cavity. But 1.05 s into the run, the cavity field jumped to its 1-photon state, stayed there for 0.48 seconds, then jumped back down.

At the cavity's 0.8-K operating temperature, one expects the mirrors' thermal fluctuations to fill the cavity with one photon for about 5% of the time. Averaging 500 runs, the ENS researchers found a slightly higher value, 6%, which they attribute to residual heating.

### The meaning of jumps

Niels Bohr introduced the concept of quantum jumps in his model of the hydrogen atom. Their probabilistic nature—states suddenly changing without cause—troubled some physicists. Quantum mechanics, they argued, is intrinsically statistical. Individual electrons in atoms don't jump.

In the 1980s physicists succeeded in trapping individual ions and looked for electrons making jumps between states. Warren Nagourney, Jon Sandberg, and Hans Dehmelt found the jumps in single barium ions. By optically monitoring the population of a metastable state, they could infer jumps between two other states.[3] And in 1999 Steven Peil and Gerald Gabrielse trapped a single electron and watched it jump between quantized cyclotron levels.[4]

When analyzed in theoretical detail, jumps turn out to spring from the appropriate Hamiltonian and the time-dependent Schrödinger equation. Far from being awkwardly instantaneous or unprovoked, jumps are an integral feature of orthodox quantum mechanics.

More recently, Wojciech Zurek of Los Alamos National Laboratory analyzed quantum jumps by following the progress of information from the system to the apparatus and the environment. According to Zurek, that flow of information, along with basic assumptions of quantum theory, inevitably breaks the unitary symmetry of Hilbert space and picks out the quantized states that the system jumps to.[5]

Brune, Haroche, Raimond, and their team are now working on a new series of experiments in which they fill the cavity with multiple photons. They hope to investigate another fundamental quantum question: the transition to classical behavior.

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### References


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## Interface between nonmagnetic insulators may be ferromagnetic and conducting

**A ferromagnetic metal would be perhaps the first of many novel electronic states that might emerge from the marriage of complex oxides.**

**In the past few decades,** researchers have focused much attention on complex oxides—oxide compounds in which the electrons interact strongly with one another and with the lattice. Such compounds exhibit a fascinating range of properties: ferromagnetism, ferroelectricity, high-temperature superconductivity, colossal magnetoresistance, and spin-glass behaviors. Not surprisingly, these compounds are being explored for myriad applications.

Interfaces between complex-oxide materials may yield even richer behavior than is found in bulk. Perhaps the interfaces exhibit phases that don't exist in either of the constituent compounds. Just look at the wide variety of electronic devices that arise from the merging of semiconductors: One striking example is the quantum Hall effect seen in the 2D electron gas formed at a gallium arsenide–aluminum gallium arsenide heterojunction.

Like semiconductors, many complex oxides are closely lattice-matched to