Physicists Trap Photons and Count Them One by One

Like a photograph on the printed page, light examined on the finest scale dissolves into grains—little bundles called photons. Although physicists have pictured light in that way for some 90 years, the experimental evidence for photons has generally been indirect or frustratingly nonintuitive. Physicists longed to actually see the discrete nature of light—"to count photons in a box, like marbles," as Serge Haroche of the Ecole Normale Supérieure (ENS) in Paris puts it. Now they can, in data from an experiment by Haroche and his colleagues.

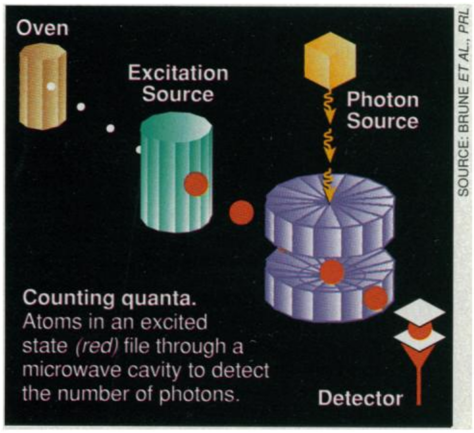
By trapping one or more photons inside a walnut-sized reflecting cavity, then injecting individual atoms into the cavity to probe the photon number, the ENS group was able to provide what Jean-Michel Raimond, who co-heads the group with Haroche, calls "very direct evidence of field quantization." Peter Knight of London's Imperial College agrees. "You are really seeing the graininess of the electromagnetic field" in the behavior of the atoms after they emerge from the cavity, he says.

Knight and others are effusive about the results, which appeared in the 11 March *Physical Review Letters* (*PRL*). "It's a heroic piece of experimental physics," he says. The experiment gives physicists a visceral demonstration of one of their field's bedrock truths. And, together with other recent work probing the way individual atoms interact with quanta of energy, it may help open the way to atom-sized logic elements that could exploit quantum mechanics to process information.

The experiment culminates a history that began in 1900, when the German physicist Max Planck, struggling to make sense of the spectrum of light emitted from heated objects, deduced light's discrete nature. Support for the idea came in 1905, when Albert Einstein attributed light's ability to kick electrons from a metal surface to the existence of individual particles of light, or photons. But this "photoelectric effect" didn't clinch the case. "Even discrete photodetection—clicks on a photodetector—is not evidence for quantization of the electromagnetic field," says Haroche. He explains that a classical field, made up of continuous waves that can have any intensity, could produce the same outcome if the detector itself had a quantized response to the field.

A handful of more recent demonstrations of the quantum nature of light close any loopholes for a classical view. But these demonstrations often depend on exotic, nonintuitive effects. The ENS group set out to design an experiment that would vividly expose the quantum nature of electromagnetic radiation—microwaves, in this case.

To do so, they needed to isolate a small number of microwave photons and come up with a supersensitive way to count them. Those requirements have taken 15 years to fulfill, says team member Michel Brune. The photons' "isolation chamber" is a 3-centimeter cavity bounded by two curved mirrors, each one polished so accurately that its surface departs from a perfect curve by no more than 1/20 of the wavelength of light. The mirrors are made of niobium; cooled almost to absolute zero, it becomes a superconductor, which helps trap the microwaves. To detect the trapped photons, the group uses rubidium atoms, specially prepared in a single excited state that survives long enough to cross the cavity to a detector.



Counting quanta. Atoms in an excited state (*red*) file through a microwave cavity to detect the number of photons.

In the experiment, the atoms streamed through the cavity in single file. Along the way, each atom and the electromagnetic field in the cavity traded energy, like two pendulums linked by a spring. When the atom dropped one step down in energy, it donated energy to the microwave field; later, it could regain energy from the field and return to its former excited state. The detector counted how many atoms arrived in the excited state, and how many arrived with an energy one notch down the ladder. Atom by atom, the experimenters built up a picture of the probability that each atom would arrive in the lower state versus the time—a few tens of microseconds—it had spent in the cavity.

When the cavity was empty of radiation, the ENS group showed, the transition probability varied in a sine-wave pattern as the transit time got longer, first increasing, then decreasing, then increasing again. Each atom, it appeared, was emitting and reabsorbing microwaves as it moved across the cavity. The sine wave indicated the number of cycles of emission and reabsorption the atoms could complete before leaving the cavity. That's generally consistent with both classical and quantum pictures of light.

What's not consistent with both pictures is what happened when microwave energy was added to the cavity. In the classical picture, any addition would increase the frequency of the observed sine wave: The electromagnetic field would simply drive the atom faster. Instead, when the ENS team injected tiny amounts of microwave energy, the regular sine wave of transition probability versus time gave way to a more intricate series of peaks and troughs.

Resolved into component frequencies, the pattern revealed a set of peaks. Each peak, Haroche says, corresponds to an additional quantum of energy—another photon. "The atoms which cross the cavity are directly measuring the amplitude of the electromagnetic field," he explains, "and the fact that we find discrete frequencies is a direct manifestation of the fact that you have discrete steps of energy inside the cavity." It's an experimental "tour de force," says David Wineland of the National Institute of Standards and Technology in Boulder, Colorado.

Wineland and his colleagues are no strangers to difficult experiments, having probed quantum graininess of a different kind in what University of Oregon physicist Howard Carmichael calls "a technically marvelous experiment." In a paper that appeared in *PRL* alongside that of the ENS group, Dawn Meekhof, Wineland, and others describe how a single beryllium ion pinned at the center of an electromagnetic cage swaps quanta of energy between its internal energy state and its vibrational motion in the trap. At first glance the two experiments may seem unrelated. But in the eyes of a theorist, "these guys have done the same thing," says Joseph Eberly of the University of Rochester in New York—using atoms to probe the quantum graininess of an "oscillator," either electromagnetic or vibrational.

Both experiments also demonstrate the kind of control over the quantum world that would be needed to build the basic logic elements of quantum computers. Says Knight, "These kinds of quantum events, where you manipulate one or two atoms with one or two photons, are the very beginning, absolutely the seeds, for what may become much more important physics involving quantum information processing."

–Andrew Watson

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