QUANTUM PHYSICS

Life and death of a photon: a new way to look

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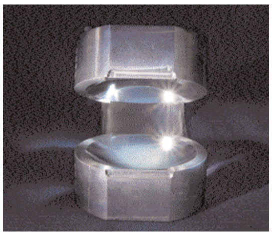
The photon is the ubiquitous particle of light which carries nearly all information we get from the outside world. It usually disappears while being detected. The retina, for instance, absorbs light, changing it into an electrical current which triggers the optical nerve. A similar phenomenon occurs on the photo-sensitive surface of usual light detectors, so that information carried by the photons is generally destroyed in the very process which records it. We certainly can see a macroscopic object as many times as we wish, but the photons which bring its image to our eye are at each time new ones.

To die while delivering its message is however not the ineluctable photon's fate. Quantum theory, which describes the behaviour of Nature at the microscopic scale, tells us that it is indeed possible to count light quanta without absorbing them, by realizing what is known as a quantum non-demolition measurement (QND for short). Non-destructive QND procedures have been successively applied to light beams containing large photon numbers, but it had not been possible so far to reach a sensitivity high enough to record repeatedly and non-destructively single light particles.

This is precisely what we have achieved recently, by implementing a QND method that we had proposed back in 1990. We have been able to observe hundreds of times the same photon trapped in a box. After a perceptible delay which can reach half a second, the light particle finally disappears, in a sudden process occurring at a random time. We have witnessed in this way the story of single photons and recorded the times of their birth and death. This experiment, whose results have recently been published in *Nature*, has required two conditions that were not fulfilled at the time of our early proposal. We had to trap light in a box for a tenth of a second on average, in order to have the time to perform repeated observations. We had also to develop a new kind of atomic detector able to record the imprint of a single photon without absorbing its energy. It has taken us several years of strenuous efforts to meet these challenges.



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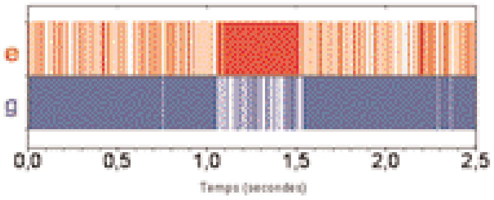
The photon box

Our microwave photon box is made of two metallic mirrors facing each other at a distance of 2.7 centimetre (see photo). The photons (which have a wavelength of about 6 millimetre) bounce more than a billion times between these mirrors before escaping through scattering on mirror's imperfections or absorption in the bulk of the metal. Such a high reflectivity, thousands of times larger than that of the best optical mirrors, is obtained by coating the mirrors with a layer of superconducting metal, cooled down to an absolute temperature below one degree. The mirrors substrate is polished with a roughness of a few nanometers only. A photon travels in this cavity over an average distance equal to the Earth circumference before vanishing. The appearance of a photon in the box is due to the radiation of its walls. Even at the very low temperature of the mirrors, their atoms have a residual thermal excitation which produces from time to time the emission of a light quantum. The laws of this so-called blackbody radiation have been first described by Planck and Einstein at the beginning of the last century. Their seminal papers have been the starting point of the quantum revolution.

The long lifetime of our photons is by itself not exceptional. In free space, a photon lives forever. The light that we receive from the outskirts of the Universe, which has travelled through empty space during billions of years is a direct evidence of the longevity of light quanta. To store for a long time a trapped photon is however very difficult. We must then have it interact with a material medium such as the reflecting walls of a cavity, or the transparent medium of an optical fibre. Under such conditions, the photon gets easily absorbed and becomes very fragile. The light quanta stored in our superconducting box set a world record for the longevity of light trapped in a small volume.

In order to observe our photons, we send one by one across the cavity rubidium atoms prepared in a very excited state known as a Rydberg state. One of the atomic electrons is promoted by laser excitation in an orbit of large size, whose radius is more than a thousand times larger than that of the electronic orbital in the atom's ground state. This very excited atom acts as a giant antenna, very sensitive to microwave radiation. An obvious way to use



Birth and death of a photon observed by the sudden changes of the atomic signal over time: the vertical bars represent an atom detected in *e* (red) or in *g* (blue). In this figure, whose size is reduced with respect to the original, bars are separated by a distance smaller than their width, giving the feeling of a continuous signal, blue for vacuum and red for one photon. Red bars on top of blue background and blue on top of red background are due to measurement errors.
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these atoms for detecting a photon is to have them absorb a light quantum while undergoing a resonant transition from an initial Rydberg state (called *g*) to a more excited level *e*. By measuring the final atomic energy, we see the photon, but by the same process, it is absorbed and thus destroyed. A new measurement will then tell us, with certainty, that the cavity is empty.

For the measurement to be QND, the photon must leave on the atom a subtler imprint. To achieve this, we render different the frequency of the photon and that of the atomic transition between states *e* and *g*. By adjusting the mirrors' separation, we slightly detune the photon from the atom. Energy conservation then prevents the atom from absorbing the light. The photon slightly changes however the frequency of the atomic transition. This light shift effect is well known in atomic physics when it is produced by intense fields. In the unusual situation which we are dealing with here, the field of a single photon shifts by a detectable amount the rotation frequency of the Rydberg electron around the atomic nucleus.

This shift is detected by a very sensitive method of atomic spectroscopy, involving auxiliary microwave fields. We subject the atom to two microwave pulses, the first before it enters the cavity, the second immediately after it leaves it. These pulses have their frequency and amplitude tuned so that their combined effect is to bring the atom from *g* to *e* provided its frequency has been shifted by a single photon in the cavity. If there is no photon, the pulses cannot induce the transition and the atom remains instead in state *g*. The energy absorbed by the atom in the former case is borrowed from the auxiliary pulses and not from the cavity field. The photon is still there after having been observed and it is ready to be seen again by another atom.

This time resolved spectroscopy procedure, invented by the physicist Norman Ramsey, is currently used in all atomic clocks. In these devices, the transition between two states of a caesium or rubidium atom is induced by a double microwave pulse, generating a signal used to lock the microwave to the atomic frequency. In this way, a very precise time standard is realized. In our experiment, each Rydberg atom is like a microscopic clock whose ticking is slightly delayed by the field of a photon. The perturbation of the clock's rate is measured by the atomic signal (atom detected in *e* when the clock has been delayed by a photon, in *g* otherwise).

The figure shows a two and a half second-long sequence during which 2500 atoms are detected either in *e* (red bars) or in *g* (blue bars). During the first second, the atoms, mostly detected in *g*, indicate that the cavity is empty (a few atoms found in *e* are due to imperfections of the set-up). The signal then suddenly changes, with a majority of atoms detected in *e*. A photon from the thermal radiation background has appeared between the mirrors. In this particular sequence, the photon survives for about half a second, i.e. more than three times the average lifetime of the photons in the cavity. It then disappears as suddenly as it appeared, leaving the cavity empty. The sudden appearances and vanishings of light occur as fast quantum jumps, at random times. Only their probability can be predicted. By recording thousands of such jumps over many hours, we have directly checked all the statistical properties of thermal radiation.

This novel non-destructive way to look illustrates a fundamental quantum process never observed so far on light, and opens fascinating perspectives. For the first time, information carried by a photon can be shared by a large number of atoms interacting one at a time with the field. It is possible to realize a situation where the cavity is in a superposition of two states, one in which it is empty, the other in which it contains a photon. To achieve this, we can send across it a first resonant atom, adjusting its interaction time with the field so that it has a 50% probability for emitting a photon. Subsequent atoms will then be detuned in order to realize a QND detection. They will finally end up in a superposition of two states, one in which they are all in *e*, the other in which they are all in *g*. This strange superposition exhibits a quantum ambiguity analogous to that of the famous Schrödinger cat which, after interacting with a single atom, ends up being at the same time alive and dead. The study of these states will help us understand better the nature of the fuzzy boundary between the quantum and the classical worlds. ■

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