# Demonstrating Single Photon Interference

*Even a single photon can manifest both wave and particle natures according to quantum theory, but demonstrating this is not so straightforward*

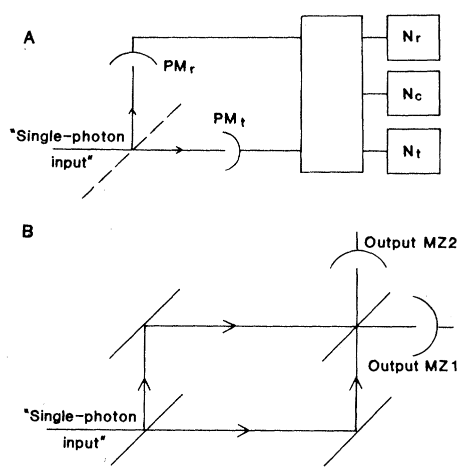
One of the hallmarks of quantum mechanics is the wave-particle duality of matter at the atomic level. Sixty years of theory and experiment provide no reason to doubt the proposition, despite the strange consequences that can follow.

Consider what happens when a single photon, the quantum of the electromagnetic field, strikes at 45 degrees an ideal half-silvered mirror; that is, an optical beam splitter. As a particle, the photon is either transmitted or reflected. As a wave, the photon is in part transmitted and in part reflected. Depending on what type of measurement follows, either the particle or the wave character of the photon manifests itself.

For example, with photodetectors directly in the transmission and reflection paths as in part A of the figure, each detector would have a 50 percent probability of recording an event, but there would be no chance of both detectors responding; that is, the photon definitely took one path or the other. However, suppose the transmission and reflection paths were first brought together and recombined by means of mirrors and a second beam splitter to form a Mach-Zehnder interferometer, as in part B of the figure. If both arms of the interferometer were the same length, photodetector $MZ_1$ would always record an event, whereas $MZ_2$ never would because of constructive and destructive interference of waves associated with *both* paths. While the quantum mechanical explanation is straightforward, it is nonetheless spooky that the type of measurement made on the photon after it passes the beam splitter appears to make the photon choose between particle and wave while it is still at the beam splitter.

Such conceptually simple experiments as these are known in the physics jargon as *gedanken* (thought) experiments. Current electronics and optical technology makes it possible to actually do some of these experiments, which were originally intended only to illustrate concepts. Last month at a meeting on quantum measurement theory, Philippe Grangier of the Institute of Theoretical and Applied Optics in Orsay, France, described a realization of the single-photon experiment that he carried out in collaboration with Gérard Roger and Alain Aspect, also of Orsay.*

A key part of the experiment was devising a single-photon source. Any other source would leave open the possibility that somehow two or more photons acting in concert were responsible for the wavelike interference. The apparently obvious approach would be to severely attenuate the intensity of a laser to the point that, on the average, less than one photon would strike the beam splitter in a given time interval. Grangier argued that this was not quite sufficient. The problem arises from the statistical properties of laser light, which, in common with all the




**Single-photon experiment**

*A photon behaves like a particle in A and a wave in B.*

optical properties of lasers, can be explained about as well in terms of classical electromagnetic waves as quantum mechanical photons.

Consider modern photodetectors that can count single "photons." The so-called second-order correlation function of an electromagnetic field measures the probability of a photodetector recording a second photon at a time delay $\tau$ after the first. A uniform value of 1, for example, would mean that the second photon is equally likely after any particular $\tau$, long or short; that is, there is always the possibility of the second photon following immediately after the first. A perfect single-photon source would have a correlation function whose value was 0 for all $\tau$'s; that is, the second photon would never come.

For classical light waves, the theoretical value of the second-order correlation function is always greater than or equal to 1. Experimentally, the value for highly coherent laser light obeys this inequality. What it comes down to is that the statistics for an attenuated laser beam do not allow with certainty the inference that there was just a single photon.

A better approximation of a single-photon source is a light source whose second-order correlation function is less than 1, at least for short $\tau$'s. Since only quantized radiation can explain values of the correlation function that are less than 1, this condition ensures being in the quantum regime where one can talk about light as a particle. More important, a value less than 1 means that photons tend to come at widely spaced intervals, which enhances the likelihood of only a single photon being present during short $\tau$'s.

The French investigators had previously built such a source for another test of quantum mechanics. It comprises a beam of calcium atoms that are irradiated by laser light. The excited atoms decay to the ground state in two steps, sequentially emitting in opposite directions two visible-wavelength photons about 4.7 nanoseconds apart. With high-speed electronics, it is possible to use detection of the first photon as a trigger to turn on photodetectors positioned to capture the second photon, which plays the role of the light emitted by the source. Under the experimental conditions, the probability of photons from another calcium atom being emitted during the same time interval and being detected is small.

Part A of the figure illustrates the experimental arrangement for demonstration of the particle nature of a single photon. A photon from the source strikes the beam splitter. A transmitted photon goes to photomultiplier tube $PM_t$, while a reflected photon goes to $PM_r$. The trigger photon opens an electronic gate for about 9 nanoseconds during which time the counting electronics can record the event. Since the argument that the source emits single photons is a statistical one, a large number of repeated experiments are run. Four quantities are tallied: the number of trigger events per second, $N_1$, the numbers of singles events per second, $N_t$ and $N_r$, in which one

*New York Academy of Sciences, "New Techniques and Ideas in Quantum Measurement Theory," New York, NY, 21 to 24 January 1986.

or the other photomultiplier tube detected a photon, and the number of coincidence events per second, $N_c$, in which both photomultiplier tubes detected photons.

From these data, it is not possible to deduce the second-order correlation function as a function of time delay, but a related quantity has the same behavior. This quantity, called $\alpha$ by Grangier, is the probability of coincidence events divided by the product of the probabilities for singles events, where the probability for each type of event is given by the number of events per second divided by the number of triggers per second. For classical radiation, including laser light, $\alpha$ is greater than or equal to 1.

At low trigger rates, the measured $\alpha$ had a value far below 1, whereas it increased toward 1 as the trigger rate grew. The experimental data closely followed the theoretical curve. In particular, at a low trigger rate of 8800 per second, after 5 hours of counting, the value of $\alpha$ was $0.18 \pm 0.06$, 13 standard deviations below the minimum classical value of 1. This corresponds to 9 coincidences per second, as compared to the classical value of 50.

Having established that the source met the single-photon criteria, the investigators turned toward verification of the wave nature of single photons. One photon at a time was allowed to pass through a Mach-Zehnder interferometer similar to that in part B of the figure. Once again, while the interference is a property of single photons, it is necessary to repeat the experiment a large number of times to generate an interference pattern. The experiment was to measure the number of counts in the outputs $MZ_1$ and $MZ_2$ as the difference in the path length through the two arms of the interferometer was varied by means of a piezoelectrically driven mechanical system. As the condition for constructive and destructive interference changed with the path length, the expected effect was a sinusoidal oscillation in the counts recorded by the two photomultipliers, with one detector being 90 degrees out of phase with the other. These intensity variations represent the interference fringes.

The path length could be controlled to about 1/50 of the wavelength of the light from the single-photon source, which was 4227 angstroms. The quality of the fringes, visibility in the jargon, is given by the ratio of the difference between the maximum and the minimum photomultiplier counts to the sum of the maximum and minimum. The experimental value of the visibility consistently was $98.7 \pm 0.5$ percent for a wide range of trigger rates, thereby verifying the wave nature of single photons. ■

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# Punctuated Equilibrium Is Now Old Hat

*The rapid changes seen in the fossil record can be accounted for by traditional explanations from population genetics, according to two recent mathematical models*

THERE is an old saying about the reception of a new idea, which goes as follows. At first it is dismissed as being wrong; then it is characterized as being against religion; and finally it is said to be something everyone knew all along. So it is with the notion of punctuated equilibrium, which has been the subject of much lively debate among evolutionary biologists for a decade and a half. This hypothesis, once rejected as being wrong or at least anti-Darwin, now appears to have entered the last of these three stages.

Using similar mathematical models of population genetics theory, two research groups independently report that the evolutionary pattern that is the basis of punctuated equilibrium—to wit, long periods of stasis of individual species in the fossil record, punctuated by bursts of rapid change—can, after all, be explained by classical Neo-Darwinian mechanisms, including selection. There is, therefore, no need to suggest that other mechanisms—such as developmental constraints—are important in influencing the pattern of change in the fossil record, they say.

Now, there are three principal aspects of these arguments. The first involves the pattern of change through time that can be inferred from the fossil record. Specifically, does change typically occur in gradual trajectories, or is it more often concentrated in rapid bursts? The second focuses on the mechanisms that shape the overall pattern of change. For instance, does selection operate to the virtual exclusion of other influences, such as developmental constraints? And the third sets the context of pattern: sometimes the environment will be changing, sometimes it will be constant.

Classical Neo-Darwinism viewed organisms as being closely adapted to their environments. It therefore followed that, when environmental conditions shifted, so too did a species' adaptations, sometimes to the point of generating a distinctly new species. There was no reason to expect—and Darwin and the Neo-Darwinians were explicit about this—that change would for the most part be other than a steady accumulation of small modifications. In other words, the pattern of change would be gradual. The fact that the fossil record does not show this—instead, it typically reveals long periods of stasis and bursts of change—has long been explained as the result of the record's woeful incompleteness. Capturing just brief glimpses of the past, it has been argued, the smooth, gradual transitions are mostly invisible in the record.

When, in 1972, Niles Eldredge, of the American Museum of Natural History, New York, and Stephen Jay Gould, of Harvard University, proposed the hypothesis of punctuated equilibrium, they were proferring two main messages.

First, that the pattern of stasis and abrupt change apparent in the fossil record is real, and not an artifact of its incompleteness. In other words, once a species has arisen it remains essentially unchanged for most of its history, but when change occurs it does so swiftly.

And second, that the long periods of stasis in individual species through periods of environmental change were not predicted by classical Neo-Darwinian theory and required another explanation. Eldredge and Gould suggested that the very conservative mechanisms of embryological development imposed constraints on the evolutionary change of a species, even in the face of some shift in environmental conditions.

The hypothesis was unpopular among classical evolutionary biologists, and was dismissed as being wrong. However, there ensued an enthusiastic search through the fossil record, focusing on organisms as small as microscopic marine species and ones as large as terrestrial vertebrates. The upshot of it all was that a complete spectrum of patterns of change could be identified, from gradual to essentially instantaneous change. It also became clear that stasis was a real phenomenon, which required explanation.

So, faced with the need to accept the reality of the pattern of punctuated equilibrium, particularly the aspect of stasis, debate began to emphasize the process by which it is produced. Just as selection can produce change, it was argued, so too can it maintain stasis, if the selection profile also remains stable. In fact, as Gould and Eldredge point out in a recent paper, this argument misses the point of the punctuated equilibrium