Wiki_double

http://en.wikipedia.org/wiki/Delayed_choice_quantum_eraser

In the basic double slit experiment: a very narrow beam of coherent light from a source that is far enough away to have almost perfectly parallel wave fronts is directed perpendicularly towards to a wall with double slits in it. The widths of the slits and the distance between them are of the same order of magnitude as the wavelength of the incident light.

If a detection screen (anything from a sheet of white paper to a digital camera) is erected on the other side of the double slit wall, a pattern of light and dark fringes, called an **interference pattern**, will be observed.

Very early in the history of this experiment, scientists discovered that they could filter out enough of the incident illumination that light reaching the detection would be observed one flash at a time. They next tried to discover by which slit a given unit of light (photon) had traveled.

Unexpectedly, the results discovered were that: if anything is done to permit determination of which path the photon takes, then, the interference pattern disappears: there is **no** interference pattern. Each photon simply hits the detector by going through one of the two slits. Each slit yields a simple single pile of hits: there is no interference pattern.

It is counterintuitive that a different outcome results based on whether or not the photon is constrained to follow one or another path well **after** it goes through the slit but before it hits the detector.

Two inconsistent accounts of the nature of light have long contended. The discovery of light's interfering with itself seemed to prove that light could not be a particle. It seemed that it had to be a wave to explain the interference seen in the double-slit (also known as Young) experiment.

But not long after this discovery, experiments with the photoelectric effect (the phenomenon that makes the light meters in cameras possible) gave equally strong evidence to support the idea that light is a particle phenomenon. Nothing is observable regarding it between the time a photon is emitted (which experimenters can at least locate in time by determining the time at which energy was supplied to the electron emitter) and the time it appears as the delivery of energy to some detector screen (such as a CCD of the emulsion of a film camera).

Nevertheless experimenters have tried to gain indirect information about which path a photon "really" takes when passing through the double-slit apparatus.

In the process what they have learned is that: constraining the path taken by one of a pair of entangled photons, inevitably controls the path taken by the partner photon. Further, if the partner photon is sent through a double-slit device and thus interferes with itself, then very surprisingly the first photon will also behave in a way consistent with its having interfered with itself, even though there is no double-slit device in its way.

In a quantum eraser experiment, one arranges to detect which one of the slits the photon passes through, but also to construct the experiment in such a way that this information can be "erased" after the fact.

In practice, this "erasure" of path information frequently means removing the constraints that kept photons following two different paths separated from each other.

In one experiment, rather than splitting one photon or its probability wave between two slits, the photon is subjected to a beam splitter. If one thinks in terms of a stream of photons being randomly directed by such a beam splitter to go down two paths that are kept from interaction, it is clear that no photon can then interfere with any other or with itself.

If the rate of photon production is reduced so that only one photon is entering the apparatus at any one time, however, it becomes impossible to understand the photon as only moving through one path because when their outputs are redirected so that they coincide on a common detector then interference phenomena appear.

In the two diagrams to the right a single photon is emitted at the yellow star, passes through a 50% beam splitter (green block) that reflects 1/2 of the photons, and travels along two possible paths, depicted by the red or blue lines.

In the top diagram, one can see that the trajectories of photons are clearly known — in the sense that if a photon emerges at the top of the apparatus it appears that it had to have come by the path that leads to that point (blue line), and if it emerges at the side of the apparatus it appears that it had to have come by way of the other path (red line).

Next, as shown in the bottom diagram: a second beam splitter is introduced at the top right. It can direct either beam towards either path; thus note that whatever emerges from each exit port may have come by way of either path.

It is in this sense that the path information has been "erased."

Note that total phase differences are introduced along the two paths because of the different effects of passing through a glass plate, being reflected off its first surface, or passing through the back surface of a semi-silvered beam splitter and being reflected by the back (inner side) of the reflective surface.

The result is that waves pass out of both the top upwards exit, and also the top-right exit. Specifically, waves passing out the top exit interfere destructively, whereas waves passing out the upper right side exit interfere constructively.

(See Mach-Zehnder interferometer for a more detailed explanation of the phase changes involved here.)

Now it seems that, regardless of appearances, something may in all cases **have traveled along both paths**. The experiment depicted above is reported in full in http://www.sciencemag.org/cgi/content/full/315/5814/966.

But what if the choice to "erase" the information is in fact delayed, until **after** the target phase?

Kim, et al., have shown that it is possible to delay the choice to "erase" the quantum information until after the photon has actually hit its target.

Under those conditions an interference pattern **can be** recovered, *even if the information is erased after the photons have hit the detector.* The experimental apparatus is considerably more elaborate than that shown and described above.

If the second beam splitter in the lower diagram could be inserted or removed one might assert that a photon must have traveled by way of one path or the other if a photon were detected at the end of one path or the other. The appearance would be that the photon "chose" one path or the other at the only (bottom left) beam splitter, and therefore could only arrive at the respective path end.

The subjective assurance that the photon followed a single path is brought into question, however, if (after the photon has presumably "decided" which path to take) a second beam splitter then makes it impossible to say by which path the photon has traveled.

What once appeared to be a "black and white" issue now appears to be a "gray" issue. It is the mixture of two originally separated paths that constitutes what is colloquially referred to as "erasure." It is actually more like "a return to indeterminability."

The experiment

The experimental setup, described in detail in the original paper, is as follows. First, a photon is generated and passes through a double slit apparatus (vertical black line in the upper left hand corner of the diagram).

The photon goes through one (or both) of the two slits, whose paths are shown as red or light blue lines, indicating which slit the photon came through.

So far, the experiment is like a conventional two-slit experiment. However, after the slits a beta barium borate crystal (labeled as BBO) causes spontaneous parametric down conversion (SPDC), converting the photon (from either slit) into two identical entangled photons with 1/2 the frequency of the original photon.

One of these photons, referred to as the "signal" photon (look at the red and light blue lines going **upwards** from the BBO crystal), continues to the target detector called D_0. The positions where these "signal" photons detected by D_0 occur can later be examined to discover if collectively those positions form an interference pattern.

The other entangled photon, referred to as the "idler" photon (look at the red and light blue lines going **downwards** from the BBO crystal), is deflected by a Glen-Thomson prism that sends it along divergent paths depending on whether it came from slit A or slit B.

Somewhat beyond the path split, beam splitters (green blocks) are encountered that each have a 50% chance of allowing the idler to pass through and a 50% chance of causing it to be reflected. The gray blocks in the diagram are mirrors.

Because of the way the beam splitters are arranged, the idler can be detected by detectors labeled D_1, D_2, D_3 and D_4. Note that:

If it is recorded at detector D_3, then it can only have come from slit B.

If it is recorded at detector D_4 it can only have come from slit A.

But if the idler is detected at detector D_1 or D_2, it might have come from **either** slit (A or B).

Thus, which detector receives the idler photon either reveals information, or specifically does not reveal information, about the path of the signal photon with which it is entangled.

If the idler is detected at either D_1 or D_2, the which-path information has been "erased," so there is **no way of knowing** whether it (and its entangled signal photon) came from slit A or B.

Whereas, if the idler is detected at D_3 or D_4, it **is known** that it (and its entangled signal photon) came from slit A or slit B, respectively.

By using a coincidence counter, the experimenters were able to isolate the entangled signal from the overwhelming photo-noise of the laboratory - recording only events where both signal and idler photons were detected.

When the experimenters **looked only at** the signal photons whose entangled idlers were detected at D_1 or D_2, they found an interference pattern.

However, when they looked at the signal photons whose entangled idlers were detected at D_3 or similarly at D_4, **they found no interference**.

This result is similar to that of the double slit experiment, since interference is observed when it is not known which slit the photon went through, while no interference is observed when the path is known.

However, what makes this experiment possibly astonishing is that, unlike in the classic double-slit experiment, the choice of whether to preserve or erase the which-path information of the idler need not be made until *after* the position of the signal photon has already been measured by D_0.

There is never any which-path information determined directly for the photons that are detected at D_0, yet detection of which-path information by D_3 or D_4 means that no interference pattern is observed in the corresponding subset of signal photons at D_0.

The results from Kim, et al. have shown that whether the idler photon is detected at a detector that preserves its which-path information (D_3 or D_4) or a detector that erases its which-path information (D_1 or D_2) determines whether interference is seen at D_0, even though the idler photon **is not observed until after** the signal photon arrives at D_0 due to the shorter optical path for the latter.

Some have interpreted this result to mean that the delayed choice to observe or not observe the path of the idler photon will change the outcome of an event in the past. However, it should be noted that an interference pattern can only be observed *after* the idlers have been detected (i.e., at D_1 or /D_2).

Note that the total pattern of all signal photons at D_0, whose entangled idlers went to multiple different detectors, will never show interference regardless of what happens to the idler photons.[2] One can get an idea of how this works by looking carefully at both the graph of the subset of signal photons whose idlers went to detector D_1 (fig. 3 in the paper) and the graph of the subset of signal photons whose idlers went to detector D_2 (fig. 4), and observing that the peaks of the first interference pattern line up with the troughs of the second and vice versa (noted in the paper as 'a π phase shift between the two interference fringes'), so that the sum of the two will not show interference.

Discussion

In their paper, Kim, et al.[1] explain that the concept of complementarity is one of the most basic principles of quantum mechanics. According to the Heisenberg Uncertainty Principle, it is not possible to measure both precise position and momentum of a quantum particle at the same time. In other words, position and momentum are *complementary*. In 1927, Niels Bohr maintained that quantum particles have both "wave-like" behavior and "particle-like" behavior, but can exhibit one kind of behavior only under conditions that prevent exhibiting the complementary characteristics. This complementarity has come to be known as the wave-particle duality of quantum mechanics. Richard Feynman believed that the presence of these two aspects under conditions that prevent their simultaneous manifestation is the basic mystery of quantum mechanics.

The actual mechanisms that enforce complementarity vary from one experimental situation to another. In the double-slit experiment, the common wisdom is that the Heisenberg Uncertainty Principle makes it impossible to determine which slit the photon passes through without at the same time disturbing it enough to destroy the interference pattern. However, in 1982, Scully and Drühl found a way around the position-momentum uncertainty obstacle and proposed a quantum eraser to obtain which-path or particle-like information without introducing large uncontrolled phase factors to disturb the interference.[3]

Scully and Drühl found that the interference pattern disappears when which-path information is obtained, even if this information was obtained without directly observing the original photon, but that if you somehow "erase" the which-path information, the interference pattern reappears.

In the delayed choice quantum eraser discussed here, the pattern reappears even if the which-path information is erased shortly after, in time, the signal photons hit the primary detector. However, the interference pattern can only be seen retroactively once the idler photons have already been detected and the experimenter has obtained information about them, with the interference pattern being seen when the experimenter looks at particular *subsets* of signal photons that were matched with idlers that went to particular detectors.

The total pattern of signal photons at the primary detector never shows interference, so it is not possible to deduce what will happen to the idler photons by observing the signal photons alone, which would open up the possibility of gaining information faster-than-light (since one might deduce this information before there had been time for a message moving at the speed of light to travel from the idler detector to the signal photon detector) or even gaining information about the future (since as noted above, the signal photons may be detected at an earlier time than the idlers), both of which would qualify as violations of causality in physics.

In fact, a theorem proved by Phillippe Eberhard shows that if the accepted equations of quantum theory are correct, it should never be possible to experimentally violate causality using quantum effects,[4] although some physicists have speculated about the possibility that these equations might be changed in a way that would be consistent with previous experiments but which could allow for experimental causality violations.[5][6]