Can we influence certain events that occurred in the past? Interpreting 'delayed choice quantum eraser' experiment

Jai Paul Dudeja
Professor and Director, Amity University Haryana, Gurgaon 122413, India.

Received: February 08, 2019 Accepted: March 21, 2019

ABSTRACT: *The phenomenon of measurement in quantum mechanics has always baffled the world since its birth in the beginning of twentieth century. This prompted Einstein to remark, "God does not play dice", to which Niels Bohr responded, "Mr. Einstein, don't tell God what to do". It is postulated that the dynamics of any system follow the well-defined equations in quantum mechanics (Schrodinger equation, for example) until the system is measured resulting into a definite (real) value. Before this measurement, there was a probability for the system to result into any one of these values. Young's double slit experiment (discussed in this paper) is a clear example to illustrate this problem of measurement in quantum mechanics. But still, it was a case of cause and effect where the effect follows the cause. But the 'delayed choice quantum eraser' experiment performed in 1999 (and published in 2000) appeared to shatter the cause-and-effect theory. It appeared that the effect took place before the cause. Many philosophers jumped into the fray (irrespective of their grip on quantum mechanics or quantum entanglement) to interpret this experiment. Some claimed that this is the demonstration of 'backward travel of time'. We interpret and discuss this experiment scientifically and logically in this paper and uncover any mystery to disagree with the claims of these 'so-called' philosophers.*

Key Words: *delayed choice quantum eraser, double-slit experiment, quantum entanglement, Consciousness, time paradox, measurement in quantum mechanics*

1. Introduction

One of the most fundamental problems for understanding of quantum mechanics is the problem of measurement. According to the Copenhagen interpretation, largely devised during 1925-1927 by Niels Bohr and Werner Heisenberg, physical systems generally do not have definite properties prior to being measured, and quantum mechanics can only predict the probability distribution of a given measurement's possible results. The act of measurement affects the system, disturbs the system due to interaction between the measuring system and the physical parameter to be measure, thus causing the set of probabilities to reduce to only one of the possible values immediately after the measurement. This feature is known as wave function collapse (WFC).

Some of the basic principles of Copenhagen interpretation are: (i) a wave function, ψ, represents the state of the system. (ii) It gives the whole information about it before any observation is made on the system. (iii) The wave function evolves smoothly in time (according to Schrodinger's equation, for example) while isolated from other systems. (iv) The description given by the wave function is probabilistic, according to Max Born and remains so, as long as no observation is made on the system. (v) During an observation, the system must interact with a measuring device. When that device makes a measurement, the wave function of the system is said to collapse, or irreversibly reduces to an eigen-state of the observable that is registered. (vi) The value of the measurement so obtained is real and is called the eigen-value of that state. (vii) The wave function expresses a necessary and fundamental wave–particle duality. (viii) An experiment can show particle-like properties, or wave-like properties, according to the complementarily principle of Niels Bohr. (ix) It can be seen that the inner workings of atomic and subatomic processes are necessarily and essentially inaccessible to direct observation, because the act of observing them would greatly affect them.

To summarize, the measurement problem in quantum mechanics can be expressed in the following way: Before being measured, the physical state of any system (that is, the wave function) evolves continuously according to the Schrödinger equation (say) as a linear superposition of eigen-states. After a measurement is taken, the linear evolution is interrupted, the wave function collapses and the superposition of states is projected onto a single determinate eigen-state.

The double-slit experiment is a demonstration that the light and matter can display characteristics of both classically defined waves and particles; and it displays the fundamentally probabilistic nature of quantum mechanical phenomena. The experiment was first performed with light by Thomas Young in 1801. He could establish the wave theory of light at that time as there was no quantum physics (dual nature) existing during Young's times. In the modern version of this experiment, a coherent light source, such as a laser beam, illuminates a plate pierced by two parallel slits, and the light passing through the slits is observed on a screen behind the plate. The wave nature of light causes the light waves passing through the two slits to interfere, producing bright and dark bands on the screen — a result that would not be expected if light consisted of classical particles. If we place a detector in front of any one of the slits just to check the trajectory of the photons, we shall find that there will be no interference pattern any more on the screen, and thus the particle nature of the photons will be displayed. This (later) act will also result into the collapse of the wave function from the probabilistic one to the deterministic state. The same experiment for demonstration of the wave-particle duality can also be done with other micro-particles like electrons, thus displaying the complementary nature of waves and particles.

This phenomenon of wave-particle duality was also a display of cause-effect theory. It means the effect will follow the cause. For example, if we do not place any detector in front of any of the slits in the double-slit experiment, it will result into the display of interference pattern on the screen across these two slits, which is a demonstration of the probabilistic nature of the wave function. But when we insert a detector in front of any of the slits, the wave function collapses and the particle nature of the light is displayed with the disappearance of any interference pattern on the screen, which was due to wave nature of photons.

This concept of the effect following the cause was shattered when the 'delayed choice quantum eraser' experiment was proposed by Kim et al [1], the focus of our discussion in this paper, in which the light was split into two entangled photons ('signal' photon and the 'idler' photon) and made to travel in different directions. The signal photon was received by a single detector and no interference was (obviously) seen. The strange part was demonstrated when the same signal photon, which earlier showed no interference pattern, was made to display so at a subsequent time when commanded by the idler photon under certain conditions. This appears as if the idler photon travels backward in time, gives a command to the signal photon, and the signal photon (in collaboration with the future idler photon) displays the interference phenomenon. If we extend this delay of a few nanoseconds to a few millions of light years (say), we could send a command to the photons which emanated from a particular star earlier, to modify their behaviour now and interact with the photons in our laboratory on the planet earth in a certain dictated way. It appears, from this, that we have now been able to influence the behaviour of the photons which were emitted millions of light years earlier. This shakes our ground and its implications will be discussed, in details, in this paper.

2. Double-Slit Experiment and its Interpretation

Figure 1 depicts the schematic of the Double-slit experiment for the light. Photons are emitted from the source of light and pass through one or both the slits behind which is a screen to see if there is any interference pattern.

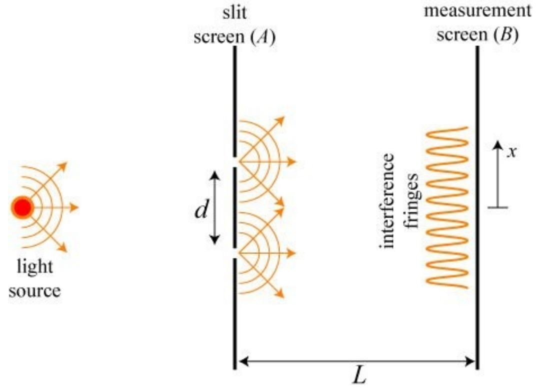

Fig. 1: Double-slit Experiment

According to this, the photons (or electrons, or anything), even individual ones behave like waves when there is no detector to determine which slit they traveled through. No detector present means that the observer does not track which-path or the trajectory is taken by the photon. The interference pattern appears in this case. The objects behave like particles when there is a detector present in front of any one of the slits. In this case, there is no interference pattern on the screen. By placing a detector in front of any one of the slits leads to the perturbation to the system in search of the so-called `which-path information' that `collapses the wave function', making interference effects disappear.

From this discussion it seems that ***the photon has got its own consciousness and intelligence, which it uses to trick the observer to hide its actual trajectory.*** Philosophically speaking, one might comment that none of these photons like to be spied upon by finding their 'which-path trajectory', and therefore, these photons refuse to reveal the other attribute of their picture (wavelike) to the observer when detectors are placed to locate them. To quote Wheeler [2]: these experiments of the double-slit are attempts to decide whether light somehow "senses" the experimental apparatus in the double-slit experiment whether it will travel through and adjusts its behavior to fit by assuming the appropriate determinate state for it, or whether light remains in an indeterminate state, neither wave nor particle, and responds to the "questions" asked of it by responding in either a wave-consistent manner or a particle-consistent manner depending on the experimental arrangements that ask these "questions".

3. Delayed Choice Quantum Eraser Experiment and its Interpretation

'Which-path information' and the visibility of interference fringes are hence complementary quantities. In the double-slit experiment, conventional wisdom held that observing the particles inevitably disturbed them enough to destroy the interference pattern as a result of the Heisenberg's uncertainty principle. However, in 1982, Scully and Druhl found a loophole around this interpretation [3]. They proposed a "quantum eraser" to obtain which-path information without scattering the particles or otherwise introducing uncontrolled phase factors to them.

A delayed-choice quantum eraser experiment, first performed by Kim et al [1], is an elaboration on the quantum eraser experiment that incorporates concepts considered in Wheeler's delayed-choice experiment [2]. The experiment was designed to investigate peculiar consequences of the well-known double-slit experiment in quantum mechanics, as well as the consequences of quantum entanglement. Rather than attempting to observe which photon was entering each slit (thus disturbing them), they proposed to "mark" them with information that, in principle at least, would allow the photons to be distinguished after passing through the slits. Lest there should be any misunderstanding, the interference pattern does disappear when the photons are so marked. However, the interference pattern reappears if the which-path information is further manipulated after the marked photons have passed through the double slits to obscure the which-path markings.

Figure 2 displays the schematic of the delayed choice quantum eraser experiment.

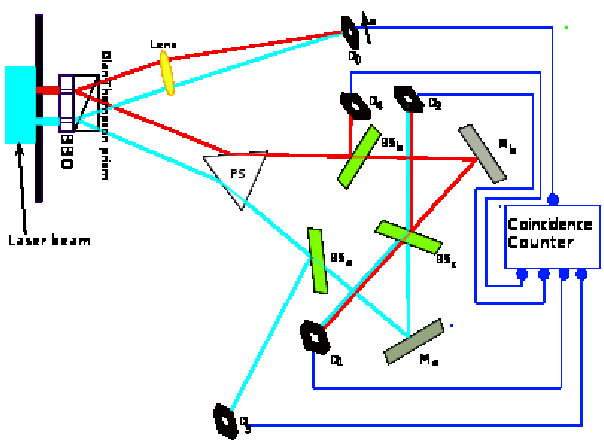

Fig. 2: 'Delayed Choice Quantum Eraser' Experiment

In a typical experiment, an argon laser generates individual 351.1 nm photons that pass through a double-slit apparatus. After the slits, the spontaneous parametric down-conversion (SPDC) is used to prepare an entangled two-photon state. This is done by a nonlinear optical crystal BBO (beta barium borate) that converts the photon (from either slit) into two identical, orthogonally polarized entangled photons, each with half the frequency (= 702.2 nm) of the original photon. The paths followed by these orthogonally polarized photons are caused to diverge by the Glan–Thompson prism. Amount of which-slit information (side of BBO crystal passed through) or interference pattern information obtained from both photons will be the same. Thus, if one of the photons of the entangled pair can later be identified by which slit it went

through, one also knows whether its entangled counterpart went through the one or the other side of the crystal. One of these 702.2 nm photons, referred to as the "signal" photon continues to the target detector called D_0. During an experiment, the detector D_0 is scanned along its x axis, its motions controlled by a step motor. A plot of "signal" photon counts detected by D_0-versus-x can be examined to discover whether the cumulative signal forms an interference pattern. The 'signal photon', reaches detector D_0 first, since path length of other photon (called the 'idler photon') is 7.7 ns longer. The presence of photon is measured at D_0, much like in the classic double-slit experiment. It is assumed that the lens does not affect the signal photon.
Note that: (i) If an idler photon is recorded at detector D_3, it can only have come from lower slit. (ii) If an idler photon is recorded at detector D_4, it can only have come from the upper slit. (iii) If an idler photon is detected at detector D_1 or D_2, it might have come from the upper slit or the lower slit. The optical path length measured from slit to D_1, D_2, D_3, and D_4 is 2.5 m longer than the optical path length from slit to D_0. This means that any information that one can learn from an idler photon must be approximately 8 ns later than what one can learn from its entangled signal photon.
Detection of the idler photon by D_3 or D_4 provides delayed "which-path information" indicating whether the signal photon with which it is entangled had gone through the upper slit or the lower slit. On the other hand, detection of the idler photon by D_1 or D_2 provides a delayed indication that such information is not available for its entangled signal photon. Insofar as which-path information had earlier potentially been available from the idler photon, it is said that the information has been subjected to a "delayed erasure". The beam splitter BS is called the eraser because if it is present, it is no more possible to know which slit the photons detected by D_1 and D_2 came from.
The experiment uses a coincidence counter to link each signal photon with its idler photon twin, after adjusting for the 8 ns delay. When the experimenters looked at the signal photons whose entangled idlers were detected at D_1 or D_2, they detected interference patterns. However, when they looked at the signal photons whose entangled idlers were detected at D_3 or D_4, they detected simple diffraction patterns with no interference.
The most important point to be noted is that the idler photon travelled approximately 8 ns longer before it could reach D_3 or D_4 to convey the message (by travelling backward in time) to the signal photon to send the message to the signal photon to display the interference phenomenon. In other words, even though an idler photon is not observed until long after its entangled signal photon arrives at D_0 due to the shorter optical path for the latter, interference at D_0 is determined by whether a signal photon's entangled idler photon is detected at a detector that preserves its which-path information (D_3 or D_4), or at a detector that erases its which-path information (D_1 or D_2). The beam splitter BS (just before the photon hits D_1 or D_2, plays the role of 'quantum eraser' of the 'which-path information' of the photon. In this experiment the 'which-path information' of the photon is obtained by the entanglement without disturbing the wave function. Significantly, the which-path information can be 'erased' long after the photon encounters the double slit. The interference pattern, as a result, reappears. To sum up, the delayed choice experiments seem to indicate that, strangely, it is possible to change the "decision" of the photons until the very last moment before they are detected.
Some people have interpreted this result to mean that the delayed choice to observe or not observe the path of the idler photon changes the outcome of an event in the past. The delayed-choice quantum eraser experiment investigates a paradox. If a photon manifests itself as though it had come by a single path to the detector, then "common sense", which Wheeler and others challenge [2], says that it must have entered the double-slit device as a particle. If a photon manifests itself as though it had come by two indistinguishable paths, then it must have entered the double-slit device as a wave. If the experimental apparatus is changed while the photon is in mid-flight, then the photon should reverse its original "decision" as to whether to be a wave or a particle. Wheeler pointed out that when these assumptions are applied to a device of interstellar dimensions, a last-minute decision made on earth on how to observe a photon could alter a decision made millions or even billions of years ago. To summarize, in the words of Wheeler [2]: "The past has no existence except that it is recorded in the present".

4. Theoretical Analysis of 'Quantum Entanglement' between Photons

A theoretical analysis of the delayed choice quantum eraser experiment will now be attempted here [4].
The incoming laser beam, in the aforementioned experiment, can be described as a plain wave and given by Eq. (1) in the following:

$$\psi = e^{ik_x x} \qquad (1),$$

incident on the double slit, where k_x is the wave vector.

After passing through the two slits, the wave function, ψ, can be written as a superposition of the two wave functions, ψ_1 and ψ_2, as given by Eq. (2):

$$\psi = \frac{1}{\sqrt{2}}(\psi_1 + \psi_2) \qquad (2)$$

It is assumed here that the wave function, ψ_1 belongs to the part of ψ, which emerges from the upper slit and the wave function, ψ_2 belongs to the part of ψ, which emerges from the lower slit.

We may assume these wave functions of the form as given by Eq. (3):

$$\psi_i = \frac{e^{ikr_i}}{r_i} \quad , \ i = 1,2 \qquad (3)$$

where r_i is the distance from the slit *i*.
Eq. (2) describes the well-known interference pattern from the double-slit experiment.

The nonlinear crystal (BBO, for example) is used to prepare an entangled two-photon state through the process of the spontaneous parametric down-conversion (SPDC); each photon with half the frequency of the original photon.
The entangled photon system is represented by Eq. (4):

$$\psi = \frac{1}{\sqrt{2}}(\psi_1 \otimes \psi_1' + \psi_2 \otimes \psi_2') \qquad (4)$$

where unprimed wave functions correspond to the 'signal photon' and primed wave functions to the 'idler photon'. The signal photon sent to the detector D_0 is now entangled to the idler photon, which is orthogonal in polarization to the signal photon, as stated earlier. This affects the probability amplitudes at D_0, and interference between ψ_1 and ψ_2 vanishes since $\psi_1 \otimes \psi_1'$ and $\psi_2 \otimes \psi_2'$ are mutually orthogonal states (note that ψ_1' *and* ψ_2' are considered to be non-overlapping and hence the interference or the cross-term vanishes).
More clearly, the squared norm of the wave function at D_0 is given by Eq. (5):

$$|\psi|^2 = \frac{1}{2}(|\psi_1|^2 |\psi_1'|^2 + |\psi_2|^2 |\psi_2'|^2) \qquad (5)$$

Assuming the signal has not yet reached D_0, if the idler gets reflected into detector D_3 the wave function would collapse to $\psi_2 \otimes \psi_2'$, and if reflected into D_4 it would collapse to $\psi_1 \otimes \psi_1'$. In case the idler photon encounters the quantum eraser, the wave function undergoes another unitary evolution. The eraser puts the idler photon in a superposition of being transmitted to one detector or reflected to the other. At each reflection at a beam-splitter or mirror the wave function picks up a phase of π/2, (a multiplication of the wave function by ($e^{i\pi/2} = i$) such that

$$\psi_1' = i\,\psi_{D1} - \psi_{D2}$$

$$\psi_2' = i\,\psi_{D2} - \psi_{D1} \qquad (6)$$

The joint wave function then turns to

$$\psi = \frac{1}{2}\left(\psi_1 \otimes (i\,\psi_{D1} - \psi_{D2}) + \psi_2 \otimes (i\,\psi_{D2} - \psi_{D1})\right)$$

$$= \frac{1}{2}((i\,\psi_1 - \psi_2) \otimes \psi_{D1} + \otimes (i\,\psi_2 - \psi_1) \otimes \psi_{D2}) \qquad (7)$$

The above equation is after the idler photon has passed the quantum eraser. Indices in ψ_{D1}, ψ_{D2} refer to which detector the part of the wave function is reflected into. In this form Eq. (7) makes it clear that when detector D_1 clicks, the wave function of the signal photon collapses to $(i\,\psi_1 - \psi_2)$, yielding a probability distribution of interference fringes,

$$|\psi_{D_0,D_1}|^2 = (i\,\psi_1 - \psi_2)(i\,\psi_1 - \psi_2)^* = |\psi_1|^2 + |\psi_2|^2 - 2\,Im(\psi_1{}^*\psi_2) \qquad (8)$$

In the case in which D_2 clicks, the wave function collapses to $(i\,\psi_2 - \psi_1)$ and yields a distribution showing anti-fringes:

$$\left|\psi_{D_0,D_2}\right|^2 = (i\,\psi_2 - \psi_1)\,(i\,\psi_2 - \psi_1)^* = |\psi_1|^2 + |\psi_2|^2 + 2\,Im\,(\psi_1{}^*\psi_2) \qquad (9)$$

In either case of detection, when travelling on one of the paths, the idler photon is reflected twice, and only once when travelling on the other.

The experiment is designed in such a way that the choice whether the wave function collapses to one which produces interference fringes or a 'no interference' pattern happens after the signal photon has been detected at D_0. We therefore say the choice is delayed. In the setup of Kim et al [1] the optical length of the idler photon is about 8 ns longer than that of the signal photon.

Crucially, at detector D_0, there never appears an interference pattern, regardless of whether the idler photon reaches the quantum eraser or not. This can readily be seen by adding up the distributions given by Eqs. (8) and (9):

$$\left|\psi_{D_0,D_1}\right|^2 + \left|\psi_{D_0,D_2}\right|^2 = 2\,(|\psi_1|^2 + |\psi_2|^2) \qquad (10)$$

The interference terms cancel out when added together which collectively leads to a clump pattern. Each sub-case (represented by Eqs. (8) and (9)) shows an interference pattern, but the overall statistics adds up to two clumps. Note that there is no way to avoid the phase difference in the interference fringes since any additional device would act symmetrically on both the paths.

So the important point to notice is that it is possible to recognize an interference pattern only through the extraction, from all the detections registered by D_0, of those corresponding either to detections by D_1 or to detections by D_2. That has the consequence that it is impossible to use this device to transmit information from the future to the past because recognizing an interference pattern is possible only when one had the knowledge of which detection by D_0 corresponds to which detector Di. In particular, the tempting idea consisting in putting or removing the beam splitter BS in the far future to produce interference (BS present) or not (BS absent) in the present, is not working because there is no way to distinguish an interference pattern from no interference just by looking at D_0 since the interference patterns correlated to D_1 and to D_2 have a π phase shift producing jointly exactly the same image than no interference at all, as is evident from Eq. (10) above. Hence it is impossible to separate them without knowing which impact corresponds to which detector and this necessitates information that can be known only after deciding to put or not the beam-splitter [5].

5. An Alternative Treatment of the Delayed Choice Quantum Eraser Experiment

The delayed choice quantum eraser can alternatively be interpreted and explained [6] quantum mechanically and there is no need to resort to the weird 'backward time travel', the view held by some. Delayed choice quantum eraser may be counter-intuitive, it may be interesting, but it is not mysterious or magical.

For convenience of explanation let us simplify the figure 2 to Fig. 3.

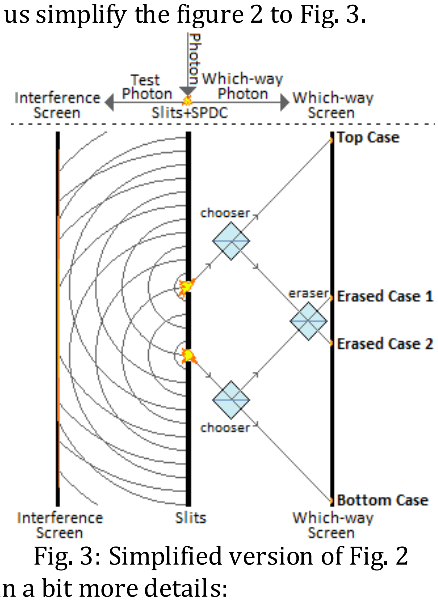

Fig. 3: Simplified version of Fig. 2

Fig. 3 is intended to communicate in a bit more details:

Entangled Superposition: A photon arrives, encounters a wall with two slits, and passes through the slits. This puts the photon's position into a superposition. Special crystals then split the photon into two photons (with entangled positions, without breaking the superposition).

One of the resulting photons does the normal double-slit thing, building up an apparent lack-of-interference pattern on the interference screen. The other photon embodies the which-way information. Its journey is represented by the right half of the diagram, and can be delayed as long as desired.

Choice: The "choice" to erase is performed by two beam splitters (the "choosers"), one for the top slit and one for the bottom slit. If the which-way photon passes through the choosers without being reflected, its impact point at the top or bottom of the which-way screen tells us which slit the original photon passed through. But if the which-way photon is reflected by the choosers then, regardless of the starting slit, an "eraser" beam splitter will distribute the photon equally between the two erased cases.

Because both the top slit and bottom slit create a 50/50 split between the two erased cases (when erased), the which-way information is lost. It cannot be recovered.

Recovery: Grouping runs of the experiment into "where the which-way photon hit" buckets reveals some interesting patterns. Within the bucket of test photons whose which-way photon went to the top case, no interference pattern is revealed. The same happens for the bottom case bucket. But the erased-case buckets filter the apparent lack-of-interference pattern we saw into two complementary interference patterns!

Here is a diagram (Fig 4) summarizing what you would see on the interference screen if you ran this experiment, and also the implied pattern within each group (which you can recover only by filtering afterwards):

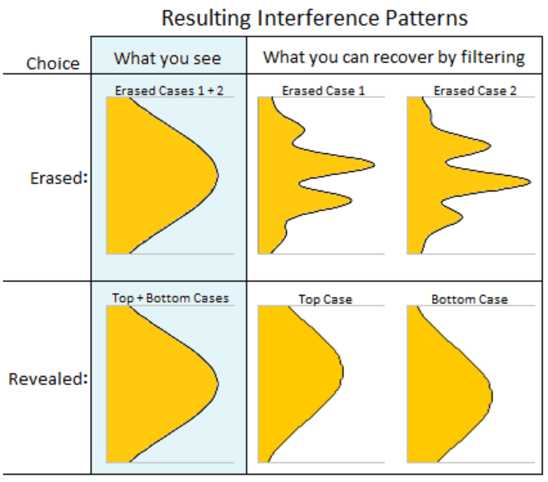

Fig. 4 : Resulting Interference Patterns

One crucial thing to notice about the above diagram is that you see the same thing in both the erased and revealed cases: a lack-of-interference pattern. You never directly see an interference pattern. The interference patterns are hidden, even in the erased cases. To find the hidden interference patterns, you need the apparently-useless which-way erased-case information. This happens because the two erased cases have complementary interference patterns: when you fail to separate them they get added together, and the ripples disappear, as reflected by Eq. (10).

The 'What you see' column of the diagram is my answer to anyone who thinks the ‘Delayed Choice Quantum Eraser’ (DCQE) can perform faster-than-light communication "because signal photon sees an interference pattern as soon as idler photon erases the which-way information". Even when idler photon erases the which-way information, the signal photon doesn't see an interference pattern. It's only when both photons get back together and compare notes that the hidden interference patterns can be revealed.

A Simplified Model

Performing DCQE does not inherently require light, and in my opinion thinking about it optically drags many unnecessary details along as baggage. DCQE is fundamentally not about photons, it is about quantum information and the odd things that happen when you try to copy it. As such, we should really be thinking in terms of qubits instead of photons. So let us translate this optical experiment into a quantum logic circuit operating on qubits. In the optical experiment, a photon is placed into a superposition of going through the upper slit or the lower slit. This can be represented by a qubit: we shall call the qubit A, use $A=|0\rangle$ to mean "went through the upper slit", and $A=|1\rangle$ to mean "went through the lower slit". Just after passing through the slits, the photon's position is in the state:

$$A= \frac{1}{\sqrt{2}}\sqrt{|0\rangle} + \frac{1}{\sqrt{2}}\sqrt{|1\rangle}.$$

Now the photon gets SPDC'd into two photons with the same position. Call the second photon B. The SPDC puts us into the state $AB=\frac{1}{\sqrt{2}}\sqrt{|00\rangle}+\frac{1}{\sqrt{2}}\sqrt{|11\rangle}$. In other words, the positions of the two photons form an EPR pair. They are entangled.

The appearance of an interference pattern (or lack thereof) can also be translated from photons to qubits. The relevant common property is coherence. When a photon is coherent, it can interfere with itself. But a decohered photon won't interfere with itself. So we can think of DCQE as playing with whether or not a photon was coherent.

Qubits can also be coherent or decohered. When a qubit is coherent, it has a "preferred direction". An experiment where you prepare a coherent qubit, then measure along the preferred direction, will give the same answer every time. A fully decohered qubit has no preferred direction. No matter which axis you measure a fully decohered qubit along, your results will look like coin flips.

It so happens that, because entanglement is suspiciously similar to measurement, qubits in an EPR pair appear to be fully decohered. It is only when you later compare results that you see they were coherent as a pair, instead of individually. DCQE is basically nothing but a reframing of this fact.

We are going to translate "does the photon make an interference pattern?" into "does measuring the qubit along different axes give probabilities other than 50/50?". We will run the qubit experiment many times, rotate qubit (A) by various amounts around the X axis, and see if the chance of getting ON when measuring A in the computational basis stays at 50% or not. Because A is part of an EPR pair, it will in fact stay at 50% and we will "conclude" that A is decohered.

After "confirming" that A is decohered, we will measure qubit B, (which was entangled with A). We will group our measurements of A into a B-was-OFF bucket and a B-was-ON bucket, and see if we can find some "hidden coherence". Two cases will be considered: one where B measures along an axis perpendicular to the ones A is using, and one where B just measures in the computational basis.

Here's what happens when B just measures in the computational basis (Fig. 5):

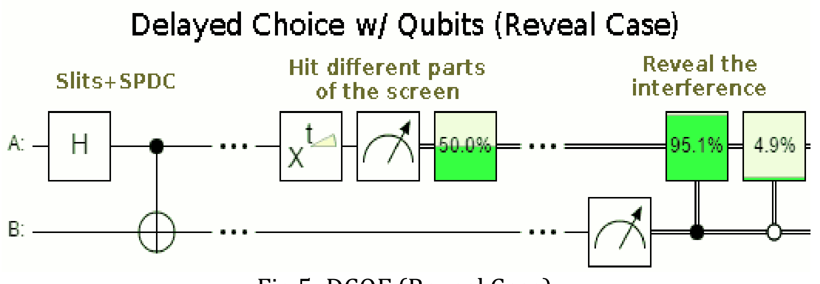

Fig 5: DCQE (Reveal Case)

As you can see above, initially 'A' concludes that the input qubits are decohered because the measurement always acts like a 50/50 coin flip even as A tries various rotations around the X axis (i.e. A "doesn't see an interference pattern"). However, because B is measuring along a similar axis, and 'A' and 'B' form an EPR pair, the results are correlated with A's (more and less, as their measurement axes go into and out of alignment).

Now for the "erased" case, where Bob measures along a perpendicular axis (Fig. 6):

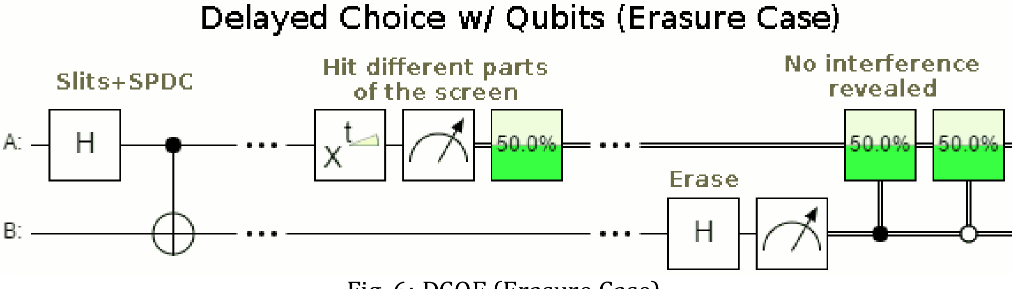

Fig. 6: DCQE (Erasure Case)

B's results are no longer correlated with A's, so grouping based on them doesn't give any predictive power. Alice concludes that her qubit was "really truly decohered".
Misconception-causing explanations of DCQE have the exact same problem, they just use a 'took-one-path' versus 'took-both-paths' dichotomy instead of a coherence dichotomy. If you check closely, you will often find qualifiers like "If you think the photon must have either taking one path or taken both paths" before the really crazy stuff.
After a detailed analysis following are the conclusions [6]:

(i) You never see an interference pattern (Refer Eq. (10)).
(ii) Backwards-in-time effects are not needed.
(iii) Consciousness has nothing to do with this.
(iv) Most of the 'weird' stuff is due to presentation of the problem.

6. Interpretation and Implication of 'Delayed Choice Quantum Eraser' Experiment

The Delayed-choice experiment discussed in this paper raises questions about time and time sequences, and thereby brings our usual ideas of time and causal sequence into question. If events at D_1, D_2, D_3, D_4 determine outcomes at D_0, then effect seems to precede cause. If the idler light paths were greatly extended so that a year goes by before a photon shows up at D_1, D_2, D_3, or D_4 , then when a photon shows up in one of these detectors, it would cause a signal photon to have shown up in a certain mode a year earlier. Alternatively, knowledge of the future fate of the idler photon would determine the activity of the signal photon in its own present. Neither of these ideas conforms to the usual human expectation of causality.
Experiments that involve entanglement exhibit phenomena that may make some people doubt their ordinary ideas about causal sequence. In the delayed-choice quantum eraser, an interference pattern will form on D_0 even if which-path data pertinent to photons that form it are only erased later in time than the signal photons that hit the primary detector. Not only that feature of the experiment is puzzling; D_0 can, in principle at least, be on one side of the universe, and the other four detectors can be "on the other side of the universe" to each other.
However, the interference pattern can only be seen retroactively once the idler photons have been detected and the experimenter has had information about them available, 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.
Moreover, the apparent retroactive action vanishes if the effects of observations on the state of the entangled signal and idler photons are considered in the historic order. Specifically, in the case when detection/deletion of which-way information happens before the detection on D_0, the standard simplistic explanation says "The detector Di, at which the idler photon is detected, determines the probability distribution at D_0 for the signal photon". Similarly, in the case when D_0 precedes detection of the idler photon, the following description is just as accurate: "The position at D_0 of the detected signal photon determines the probabilities for the idler photon to hit either of D_1, D_2, D_3 or D_4". These are just equivalent ways of formulating the correlations of entangled photons' observables in an intuitive causal way, so one may choose any of those (in particular that one, where the cause precedes the consequence and no retrograde action appears in the explanation).
The total pattern of signal photons at the primary detector never shows interference, as is evident from Eq. (10), so it is not possible to deduce what will happen to the idler photons by observing the signal photons alone. The delayed-choice quantum eraser does not communicate information in a retro-causal manner because it takes another signal, one which must arrive by a process that can go no faster than the speed of light, to sort the superimposed data in the signal photons into four streams that reflect the states of the idler photons at their four distinct detection screens.
While the delayed-choice experiments have confirmed the seeming ability of measurements made on photons in the present to alter events occurring in the past, this requires a non-standard view of quantum mechanics. If a photon in flight is interpreted as being in a so-called "superposition of states", that is, if it is interpreted as something that has the potentiality to manifest as a particle or wave, but during its time in flight is neither, then there is no time paradox. This is the standard view, and recent experiments have supported it.
The delayed choice quantum eraser experiment yields at least two possible ways to look at the ultimate nature of reality. The first: It is possible, in the quantum world, for quantum particles to cause things in the past. The particles create effects in the past. A second way to look at it arises from the transactional

interpretation of Quantum Mechanics,: quantum particles operate in a sublevel of reality, called "Quantumland." In Quantumland, particles are able to get things done which would not be possible in our physical reality. The quantum particles follow the strict, consistent laws of quantum physics. But these laws are different from those which govern the physical reality of everyday life (Newtonian physics laws).

The total pattern of signal photons at the primary detector never shows interference[Eq. (10)], so it is not possible to deduce what will happen to the idler photons by observing the signal photons alone. The delayed-choice quantum eraser does not communicate information in a retro-causal manner because it takes another signal, one which must arrive by a process that can go no faster than the speed of light, to sort the superimposed data in the signal photons into four streams that reflect the states of the idler photons at their four distinct detection screens.

7. Conclusion

In this paper we have discussed a very important phenomenon of measurement of wave-particle duality nature of photons (or electrons) in quantum mechanics. Young's double-slit experiment states that if we attempt to know 'which-path' trajectory of the particle (a photon, say) the experiment will display only the particle-nature of the photon, resulting into the collapse of the wave function. On the other hand, if we leave the system as such, even a single photon is capable of showing its wave-nature resulting into an interference pattern across a screen beyond the two slits. All said and done, this is a phenomenon where the effect follows the cause. But in the 'delayed choice quantum eraser' experiment, this cause-preceding the effect mysteriously seems to get reversed. It appears as if the 'time is traveling backwards' to cause an effect in the past. Through a detailed discussion and interpretation of this experiment, we have shown that is this not so. There is no possible retro-causality.

References

1. Kim, Yoon-Ho; R. Yu; S. P. Kulik; Y. H. Shih; Marlan Scully (2000). "A Delayed Choice Quantum Eraser", Physical Review Letters. 84 (1): 1–5.
2. Wheeler, John Archibald; Ford, Kenneth (1998). "Geons, Black Holes, and Quantum Foam: A Life in Physics". W.W. Norton & Co. ISBN 0-393-04642-7.
3. Scully, M.O., Druhl K. "Quantum eraser: A proposed photon correlation experiment concerning observation and "delayed choice" in quantum mechanics". Physical Review, A 25 (4): 1982, 2208–2213. Bibcode :1982PhRvA..25.2208S . doi : 10.1103/PhysRevA.25.2208 .
4. Fankhauser, Johannes, "Taming the Delayed Choice Quantum Eraser", Oct 5, 2018, https://arxiv.org/abs/1707.07884
5. Zwirn, Herve, "Delayed Choice, Complementarity, Entanglement and Measurement", Physics Essays, July 2016, DOI: 10.4006/0836-1398-30.3.281
6. Deflating Delayed Choice Quantum Erasure, 07 Jan 2016, https://algassert.com/quantum/2016/01/07/Delayed-Choice-Quantum-Erasure.html