Delayed choice quantum eraser

A **delayed choice quantum eraser** experiment, first performed by Yoon-Ho Kim, R. Yu, S.P. Kulik, Y.H. Shih and Marlan O. Scully,[1] and reported in early 1999, is an elaboration on the quantum eraser experiment that incorporates concepts considered in Wheeler's delayed choice experiment. 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.

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) says 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.

While 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 QM. If a photon in flight is interpreted as being in a so-called "superposition of states," i.e. 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.[2][3]

1 Introduction

In the basic double slit experiment, a beam of light (usually from a laser) is directed perpendicularly towards a wall pierced by two parallel slit apertures. If a detection screen (anything from a sheet of white paper to a CCD) is put on the other side of the double slit wall, a pattern of light and dark fringes will be observed, a pattern that is called an **interference pattern**. Other atomic-scale entities such as electrons are found to exhibit the same behavior when fired toward a double slit.[4] By decreasing the brightness of the source sufficiently, individual particles that form the interference pattern are detectable.[5] The emergence of an interference pattern suggests that each particle passing through the slits interferes with itself, and that therefore in some sense the particles are going through both slits at once.[6]:110 This is an idea that contradicts our everyday experience of discrete objects.

A well-known thought experiment, which played a vital role in the history of quantum mechanics (for example, see the discussion on Einstein's version of this experiment), demonstrated that if particle detectors are positioned at the slits, showing through which slit a photon goes, the interference pattern will disappear.[4] This *which-way* experiment illustrates the complementarity principle that photons can behave as either particles or waves, but not both at the same time.[7][8][9] However, technically feasible realizations of this experiment were not proposed until the 1970s.[10]

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 uncertainty principle.

However, in 1982, Scully and Drühl found a loophole around this interpretation.[11] They proposed a "quantum eraser" to obtain which-path information without scattering the particles or otherwise introducing uncontrolled phase factors to them. 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 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. Since 1982, multiple experiments have demonstrated the validity of the so-called quantum "eraser."[12][13][14]

1.1 A simple quantum eraser experiment

A simple version of the quantum eraser can be described as follows: 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 would

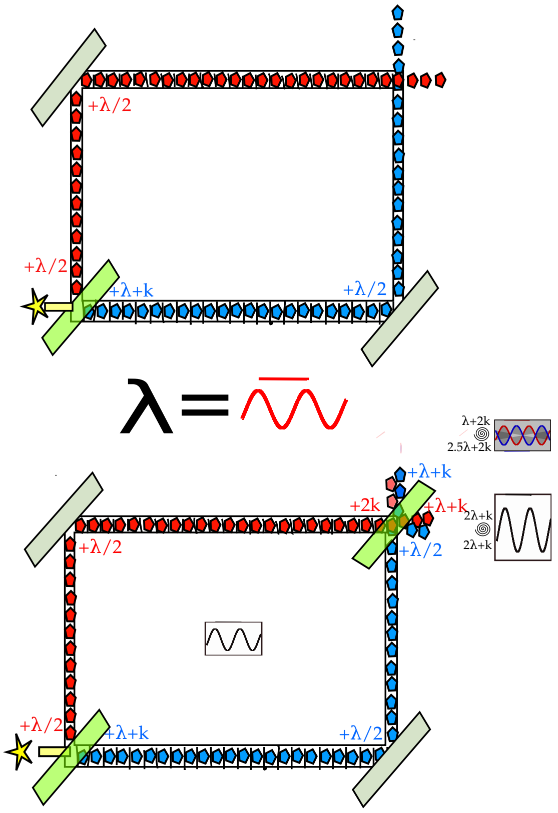

Figure 1. Experiment that shows delayed determination of photon path

seem that no photon can then interfere with any other or with itself.

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

In the two diagrams in Fig. 1, photons are emitted one at a time from a laser symbolized by a yellow star. They pass through a 50% beam splitter (green block) that reflects or transmits 1/2 of the photons. The reflected or transmitted photons travel along two possible paths depicted by the red or blue lines.

In the top diagram, the trajectories of the photons are clearly known: If a photon emerges from the top of the apparatus, it had to have come by way of the blue path, and if it emerges from the side of the apparatus, it had to have come by way of the red path.

In the bottom diagram, a second beam splitter is introduced at the top right. It can direct either beam toward either exit port. Thus, photons emerging from each exit port may have come by way of either path. By introducing the second beam splitter, the path information has been "erased". Erasing the path information results in interference phenomena at detection screens positioned just beyond each exit port. What issues to the right side displays reinforcement, and what issues toward the top displays cancellation.[15]

1.2 Delayed choice

Elementary precursors to current quantum eraser experiments such as the "simple quantum eraser" described above have straightforward classical-wave explanations. Indeed, it could be argued that there is nothing particularly quantum about this experiment.[16] Nevertheless, Jordan has argued on the basis of the correspondence principle, that despite the existence of classical explanations, first-order interference experiments such as the above can be interpreted as true quantum erasers.[17]

These precursors use single-photon interference. Versions of the quantum eraser using entangled photons, however, are intrinsically non-classical. Because of that, in order to avoid any possible ambiguity concerning the quantum versus classical interpretation, most experimenters have opted to use nonclassical entangled-photon light sources to demonstrate quantum erasers with no classical analog.

Furthermore, use of entangled photons enables the design and implementation of versions of the quantum eraser that are impossible to achieve with single-photon interference, such as the **delayed choice quantum eraser** which is the topic of this article.

2 The experiment of Kim *et al.* (2000)

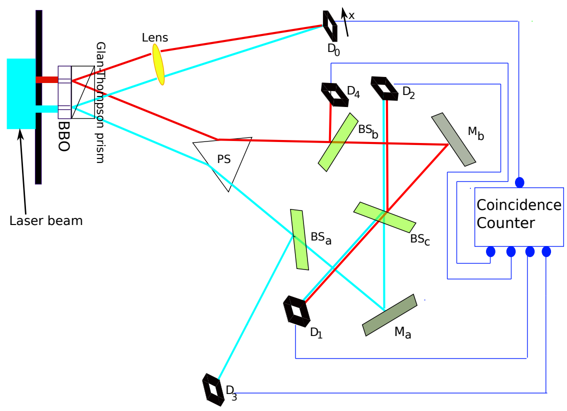

Figure 2. Setup of the delayed choice quantum eraser experiment of Kim et al. *Detector D_0 is movable*

The experimental setup, described in detail in Kim *et al.*,[1] is illustrated in Fig 2. An argon laser generates individual 351.1 nm photons that pass through a double slit apparatus (vertical black line in the upper left hand corner of the diagram).

An individual photon goes through one (or both) of the two slits. In the illustration, the photon paths are color-coded as red or light blue lines to indicate which slit the photon came through (red indicates slit A, light blue indicates slit B).

So far, the experiment is like a conventional two-slit experiment. However, after the slits, 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 with 1/2 the frequency of the original photon. The paths followed by these orthogonally polarized photons are caused to diverge by the Glan-Thompson Prism.

One of these 702.2 nm photons, referred to as the "signal" photon (look at the red and light-blue lines going *upwards* from the Glan-Thompson prism) continues to the target detector called D_0. During an experiment, 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 other entangled photon, referred to as the "idler" photon (look at the red and light-blue lines going *downwards* from the Glan-Thompson prism), is deflected by prism *PS* that sends it along divergent paths depending on whether it came from slit *A* or slit *B*.

Somewhat beyond the path split, the idler photons encounter beam splitters BS_a, BS_b, and BS_c that each have a 50% chance of allowing the idler photon to pass through and a 50% chance of causing it to be reflected. M_a and M_b are mirrors.

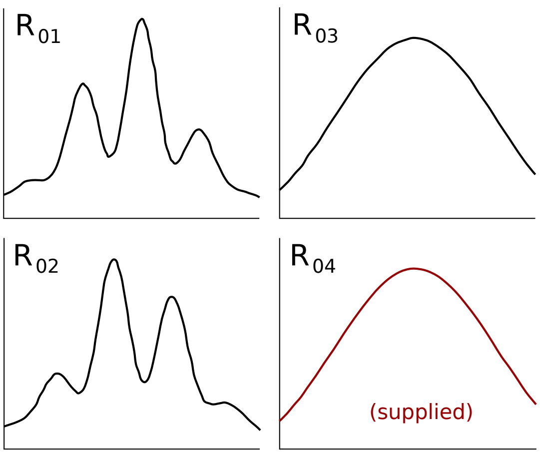

Figure 3. ***x axis****: position of* D_0. ***y axis****: joint detection rates between* D_0 *and* D_1, D_2, D_3, D_4 *(*R_{01}, R_{02}, R_{03}, R_{04}*).* R_{04} *is not provided in the Kim article, and is supplied according to their verbal description.*

The beam splitters and mirrors direct the idler photons towards detectors labeled D_1, D_2, D_3 and D_4. Note that:

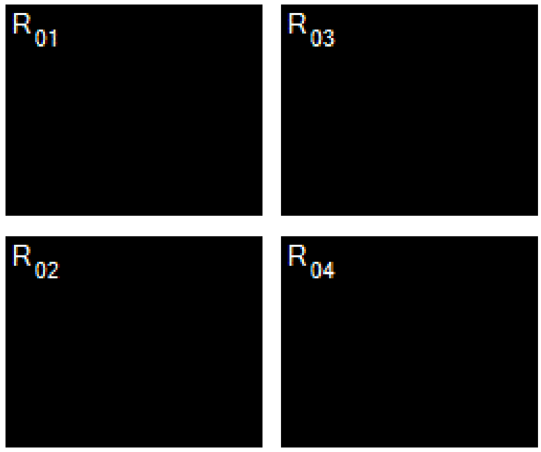

Figure 4. Simulated recordings of photons jointly detected between D_0 *and* D_1, D_2, D_3, D_4 *(*R_{01}, R_{02}, R_{03}, R_{04}*)*

- If an idler photon is recorded at detector D_3, it can only have come from slit B.
- If an idler photon is recorded at detector D_4, it can only have come from slit A.
- If an idler photon is detected at detector D_1 or D_2, it might have come from slit A or slit B.
- 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 slit A or B. 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".

By using a coincidence counter, the experimenters were able to isolate the entangled signal from photo-noise, recording only events where both signal and idler photons were detected (after compensating for the 8 ns delay). Refer to Figs 3 and 4.

- 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.

2.1 Significance

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.

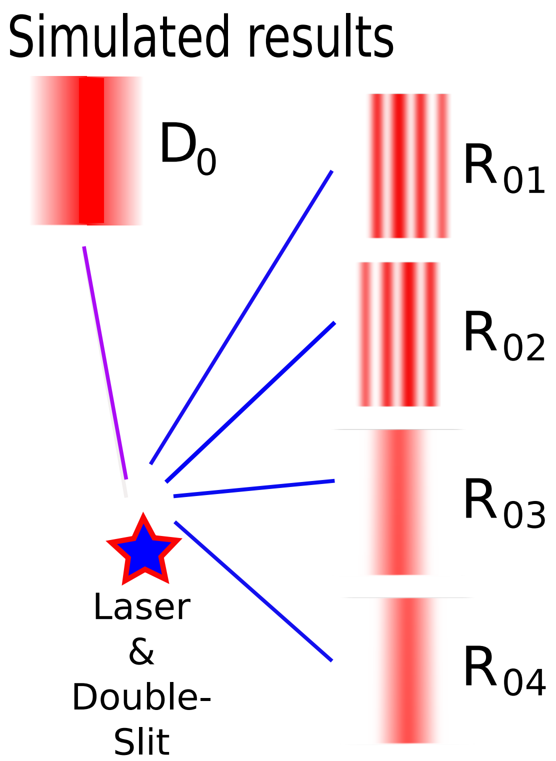

Figure 5. Distribution of signal photons at D_0 *can be compared with distribution of bulbs on* digital billboard*. When all the bulbs are lit, billboard won't reveal any pattern of image, which can be 'recovered' only by switching-off some bulbs. Likewise interference pattern or no-interference pattern among signal photons at* D_0 *can be recovered only after 'switching-off' (or ignoring) some signal photons and which signal photons should be ignored to recover pattern, this information can be gained only by looking at corresponding entangled idler photons in detectors* D_1 *to* D_4.

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 was not made until 8 ns *after* the position of the signal photon had already been measured by D_0.

Detection of signal photons at D_0 does not directly yield any which-path information. Detection of idler photons at D_3 or D_4, which provide which-path information, means that no interference pattern can be observed in the jointly detected subset of signal photons at D_0. Likewise, detection of idler photons at D_1 or D_2, which do not provide which-path information, means that interference patterns *can* be observed in the jointly detected subset of signal photons at D_0.

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).

Some 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. However, the consensus contemporary position is that retrocausality is not necessary to explain the phenomenon of delayed choice. [18] Note in particular that an interference pattern may only be pulled out for observation *after* the idlers have been detected (*i.e.*, at D_1 or D_2).

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.[19] One can get an idea of how this works by looking at the graphs of R_{01}, R_{02}, R_{03}, and R_{04}, and observing that the peaks of R_{01} line up with the troughs of R_{02} (*i.e.* a π phase shift exists between the two interference fringes). R_{03} shows a single maximum, and R_{04}, which is experimentally identical to R_{03} will show equivalent results. The entangled photons, as filtered with the help of the coincidence counter, are simulated in Fig. 5 to give a visual impression of the evidence available from the experiment. In D_0, the sum of all the correlated counts will not show interference. If all the photons that arrive at D_0 were to be plotted on one graph, one would see only a bright central band.

3 Implications

3.1 Possibility of retrocausality

Delayed choice experiments raise questions about time and time sequences, and thereby bring our usual ideas of time and causal sequence into question.[note 1] 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. However, knowledge of the future, which would be a hidden variable, was refuted in experiments.[20]

3.2 Does delayed choice violate 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 hit that 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.[21]:197f

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.[21]:197

The total pattern of signal photons at the primary detector never shows interference (see Fig. 5), 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 via 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.[note 2][note 3]

In fact, a theorem proved by Phillippe Eberhard shows that if the accepted equations of relativistic quantum field theory are correct, it should never be possible to experimentally violate causality using quantum effects.[22] (See reference[23] for a treatment emphasizing the role of conditional probabilities.)

In addition to challenging our common sense ideas of temporal sequence in cause and effect relationships, this experiment is among those that strongly attack our ideas about locality, the idea that things cannot interact unless they are in contact, if not by being in direct physical contact then at least by interaction through magnetic or other such field phenomena.[21]:199

3.3 Against consensus

Despite Eberhard's proof, some physicists have speculated that these experiments might be changed in a way that would be consistent with previous experiments, yet which could allow for experimental causality violations.[24][25][26]

4 Other delayed choice quantum eraser experiments

Many refinements and extensions of Kim *et al.*'s delayed choice quantum eraser have been performed or proposed. Only a small sampling of reports and proposals are given here:

Scarcelli *et al.* (2007) reported on a delayed-choice quantum eraser experiment based on a two-photon imaging scheme. After detecting a photon which passed through a double-slit, a random delayed choice was made to erase or not erase the which-path information by the measurement of its distant entangled twin; the particle-like and wave-like behavior of the photon were then recorded simultaneously and respectively by only one set of joint detectors.[27]

Peruzzo et al. (2012) have reported on a quantum delayed choice experiment, based on a quantum controlled beam-splitter, in which particle and wave behaviors were investigated simultaneously. The quantum nature of the photon's behavior was tested via a Bell inequality, which replaced the delayed choice of the observer.[28]

The construction of solid state electronic Mach-Zehnder interferometers (MZI) has led to proposals to use them in electronic versions of quantum eraser experiments. This would be achieved by Coulomb coupling to a second electronic MZI acting as a detector.[29]

Entangled pairs of neutral kaons have also been examined and found suitable for investigations using quantum marking and quantum erasure techniques.[30]

5 Notes

[1] Stanford Encyclopedia of Philosophy, "More recently, the Bell type experiments have been interpreted by some as if quantum events could be connected in such a way that the past light cone might be accessible under non-local interaction; not only in the sense of action at a distance but as backward causation. One of the most enticing experiments of this kind is the Delayed Choice Quantum Eraser designed by Yoon-Ho Kim et. al (2000). It is a rather complicated construction. It is set up to measure correlated pairs of photons, which are in an entangled state, so that one of the two photons is detected 8 nanoseconds before its partner. The results of the experiment are quite amazing. They seem to indicate that the behavior of the photons detected these 8 nanoseconds before their partners is determined by how the partners will be detected. Indeed it might be tempting to interpret these results as an example of the future causing the past. The result is, however, in accordance with the predictions of quantum mechanics." http://plato.stanford.edu/entries/causation-backwards/

[2] "... the future measurements do not in any way change the data you collected today. But the future measurements *do* influence the kinds of details you can invoke when you subsequently describe what happened today. Before you have the results of the idler photon measurements, you really can't say anything at all about the which-path history of any given signal photon. However, once you have the results, you conclude that signal photons whose idler partners were successfully used to ascertain which-path information *can* be described as having ... traveled either left

or right. You also conclude that signal photons whose idler partners had their which-path information erased *cannot* be described as having ... definitely gone one way or the other (a conclusion you can convincingly confirm by using the newly acquired idler photon data to expose the previously hidden interference pattern among this latter class of signal photons). We thus see that the future helps shape the story you tell of the past." — Brian Greene, *The Fabric of the Cosmos*, *pp* 198–199

[3] The Kim paper says:
P. 1f: The experiment is designed in such a way that L0, the optical distance between atoms A, B and detector D_0, is much shorter than Li, which is the optical distance between atoms A, B and detectors D_1, D_2, D_3, and D_4, respectively. So that D_0 will be triggered much earlier by photon 1. After the registration of photon 1, we look at these "delayed" detection events of D_1, D_2, D_3, and D_4 which have constant time delays, i ≃ (Li – L0)/c, relative to the triggering time of D_0. **P.2:** In this experiment the optical delay (Li – L0) is chosen to be ≃ 2.5m, where L0 is the optical distance between the output surface of BBO and detector D_0, and Li is the optical distance between the output surface of the BBO and detectors D_1, D_2, D_3, and D_4, respectively. This means that any information one can learn from photon 2 must be at least 8ns later than what one has learned from the registration of photon 1. Compared to the 1ns response time of the detectors, 2.5m delay is good enough for a "delayed erasure". **P. 3:** The which-path or both-path information of a quantum can be erased or marked by its entangled twin even after the registration of the quantum. **P. 2:** After the registration of photon 1, we look at these "delayed" detection events of D_1, D_2, D_3, and D_4 which have constant time delays, i ≃ (Li – L0)/c, relative to the triggering time of D_0. **It is easy to see these "joint detection" events must have resulted from the same photon pair.** (Emphasis added. This is the point at which what is going on at D_0 can be figured out.)

6 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**: 1–5. arXiv:quant-ph/9903047. Bibcode:2000PhRvL..84....1K. doi:10.1103/PhysRevLett.84.1.

[2] Ma, Zeilinger, et al., "Quantum erasure with causally disconnected choice." See: http://www.pnas.org/content/110/4/1221 "Our results demonstrate that the viewpoint that the system photon behaves either definitely as a wave or definitely as a particle would require faster-than-light communication. Because this would be in strong tension with the special theory of relativity, we believe that such a viewpoint should be given up entirely. "

[3] Peruzzo, et al., "A quantum delayed choice experiment," arXiv:1205.4926v2 [quant-ph] 28 Jun 2012. This experiment uses Bell inequalities to replace the delayed choice devices, but it achieves the same experimental purpose in an elegant and convincing way.

[4] Feynman, Richard P.; Robert B. Leighton; Matthew Sands (1965). *The Feynman Lectures on Physics, Vol. 3*. US: Addison-Wesley. pp. 1.1–1.8. ISBN 0-201-02118-8.

[5] Donati, O; Missiroli, G F; Pozzi, G (1973). "An Experiment on Electron Interference". *American Journal of Physics* **41**: 639–644. doi:10.1119/1.1987321.

[6] Greene, Brian (2003). *The Elegant Universe*. Random House, Inc. ISBN 0-375-70811-1.

[7] Harrison, David (2002). "Complementarity and the Copenhagen Interpretation of Quantum Mechanics". *UPSCALE*. Dept. of Physics, U. of Toronto. Retrieved 2008-06-21.

[8] Cassidy, David (2008). "Quantum Mechanics 1925–1927: Triumph of the Copenhagen Interpretation". *Werner Heisenberg*. American Institute of Physics. Retrieved 2008-06-21.

[9] Boscá Díaz-Pintado, María C. (29–31 March 2007). "Updating the wave-particle duality". *15th UK and European Meeting on the Foundations of Physics*. Leeds, UK. Retrieved 2008-06-21.

[10] Bartell, L. (1980). "Complementarity in the double-slit experiment: On simple realizable systems for observing intermediate particle-wave behavior". *Physical Review D* **21** (6): 1698–1699. Bibcode:1980PhRvD..21.1698B. doi:10.1103/PhysRevD.21.1698.

[11] Scully, Marlan O.; Kai Drühl (1982). "Quantum eraser: A proposed photon correlation experiment concerning observation and "delayed choice" in quantum mechanics". *Physical Review A* **25** (4): 2208–2213. Bibcode:1982PhRvA..25.2208S. doi:10.1103/PhysRevA.25.2208.

[12] Zajonc, A. G.; Wang, L. J.; Zou, X. Y.; Mandel, L. (1991). "Quantum eraser". *Nature* **353**: 507–508. Bibcode:1991Natur.353..507Z. doi:10.1038/353507b0.

[13] Herzog, T. J.; Kwiat, P. G.; Weinfurter, H.; Zeilinger, A. (1995). "Complementarity and the quantum eraser" (PDF). *Physical Review Letters* **75** (17): 3034–3037. Bibcode:1995PhRvL..75.3034H. doi:10.1103/PhysRevLett.75.3034. Retrieved 13 February 2014.

[14] Walborn, S. P.; et al. (2002). "Double-Slit Quantum Eraser". *Phys. Rev. A* **65** (3): 033818. arXiv:quant-ph/0106078. Bibcode:2002PhRvA..65c3818W. doi:10.1103/PhysRevA.65.033818.

[15] Jacques, Vincent; Wu, E; Grosshans, Frédéric; Treussart, François; Grangier, Philippe; Aspect, Alain; Rochl, Jean-François (2007). "Experimental Realization of Wheeler's Delayed-Choice Gedanken Experiment". *Science* **315** (5814): 966–968. arXiv:quant-ph/0610241. Bibcode:2007Sci...315..966J. doi:10.1126/science.1136303. PMID 17303748.

[16] Chiao, R. Y.; P. G. Kwiat; Steinberg, A. M. (1995). "Quantum non-locality in two-photon experiments at Berkeley". *Quantum and Semiclassical Optics: Journal of the European Optical Society*

Part B **7** (3): 259–278. arXiv:quant-ph/9501016. Bibcode:1995QuSOp...7..259C. doi:10.1088/1355-5111/7/3/006. Retrieved 13 February 2014.

[17] Jordan, T. F. (1993). "Disppearance and reappearance of macroscopic quantum interference". *Physical Review A* **48** (3): 2449–2450. Bibcode:1993PhRvA..48.2449J. doi:10.1103/PhysRevA.48.2449.

[18] Ionicioiu, R.; Terno, D. R. (2011). "Proposal for a quantum delayed-choice experiment". *Phys. Rev. Lett.* **107**: 230406. arXiv:1103.0117. Bibcode:2011PhRvL.107w0406I. doi:10.1103/physrevlett.107.230406.

[19] Greene, Brian (2004). *The Fabric of the Cosmos: Space, Time, and the Texture of Reality*. Alfred A. Knopf. p. 198. ISBN 0-375-41288-3.

[20] "A quantum delayed choice experiment" (PDF).

[21] Greene, Brian (2004). *The Fabric of the Cosmos*. Alfred A. Knopf. ISBN 0-375-41288-3.

[22] Eberhard, Phillippe H.; Ronald R. Ross (1989). "Quantum field theory cannot provide faster-than-light communication". *Foundations of Physics Letters* **2** (2): 127–149. Bibcode:1989FoPhL...2..127E. doi:10.1007/BF00696109.

[23] Bram Gaasbeek. Demystifying the Delayed Choice Experiments. arXiv preprint, 22 July 2010.

[24] John G. Cramer. NASA Goes FTL - Part 2: Cracks in Nature's FTL Armor. "Alternate View" column, Analog Science Fiction and Fact, February 1995.

[25] Paul J. Werbos, Ludmila Dolmatova. The Backwards-Time Interpretation of Quantum Mechanics - Revisited With Experiment. arXiv preprint, 7 August 2000.

[26] John Cramer, "An Experimental Test of Signaling using Quantum Nonlocality" has links to several reports from the University of Washington researchers in his group. See: http://faculty.washington.edu/jcramer/NLS/NL_signal.htm

[27] Scarcelli, G.; Zhou, Y.; Shih, Y. (2007). "Random delayed-choice quantum eraser via two-photon imaging" (PDF). *The European Physical Journal D* **44** (1): 167–173. Bibcode:2007EPJD...44..167S. doi:10.1140/epjd/e2007-00164-y.

[28] Peruzzo, A.; Shadbolt, P.; Brunner, N.; Popescu, S.; O'Brien, J. L. (2012). "A quantum delayed-choice experiment". *Science* **338**: 634–637. arXiv:1205.4926. Bibcode:2012Sci...338..634P. doi:10.1126/science.1226719. Retrieved 14 February 2014.

[29] Dressel, J.; Choi, Y.; Jordan, A. N. (2012). "Measuring which-path information with coupled electronic Mach-Zehnder interferometers". *Physical Review B* **85** (4): 045320. doi:10.1103/physrevb.85.045320. Retrieved 14 February 2014.

[30] Bramon, A.; Garbarino, G.; Hiesmayr, B. C. (2004). "Quantum marking and quantum erasure for neutral kaons". *Physical Review Letters* **92** (2): 020405. arXiv:quant-ph/0306114. Bibcode:2004PhRvL..92b0405B. doi:10.1103/physrevlett.92.020405. Retrieved 14 February 2014.

7 External links

- presentation of the experiment
- basic delayed choice experiment
- delayed choice quantum eraser
- the notebook of philosophy and physics
- Comprehensive experimental test of quantum erasure, Alexei Trifonov, Gunnar Bjork, Jonas Soderholm, and Tedros Tsegaye (doi:10.1140/epjd/e20020030)
- A non-local quantum eraser (June 2012; 12 authors, including Anton Zeilinger)
- Delayed Choice Quantum Eraser Experiment Explained, YouTube (with an explanation of the experiment by Kim et al. in minutes 3:31 to 9:09)

8 Text and image sources, contributors, and licenses

8.1 Text

- **Delayed choice quantum eraser** *Source:* https://en.wikipedia.org/wiki/Delayed_choice_quantum_eraser?oldid=711561543 *Contributors:* Stevertigo, Patrick0Moran, Rursus, Giftlite, Dratman, Elektron, Chris Howard, El C, Avian, Bobrayner, Linas, GregorB, Plrk, Rjwilmsi, Lotu, Archelon, Mysid, IceWeasel, Tzepish, That Guy, From That Show!, SmackBot, Alan McBeth, Lostart, Rich.lewis, AstroChemist, Mr Stephen, Hypnosifl, Checkguy, UncleDouggie, Tawkerbot2, Hkyriazi, Michael C Price, DumbBOT, Headbomb, Widefox, Sidb, Original-name37, KellyArt, Barraki, Ummonk, Iosef, DParlevliet, Mihaimai, Kpedersen1, Lamro, Bporopat, Jacotto, Yone Fernandes, Martarius, Canopus1, Fjados, RenamedUser jaskldjslak901, DumZiBoT, Midnight Voice, Drlight11, Addbot, DOI bot, Endogenous -i, AnomieBOT, OrbitTheSun, Citation bot, Qorilla, FrescoBot, Paine Ellsworth, Pablonimer, Citation bot 1, Trappist the monk, Callanecc, Michael9422, TASagent, NotAnonymous0, Gradatmit, TonyMath, RockMagnetist, ClueBot NG, Bbbbbbbbba, Bibcode Bot, BG19bot, Blaspie55, BattyBot, Stigmatella aurantiaca, Dexbot, Fixuture, ClearConcise, Monkbot, Yakamashi, IONS-RJP, Ajkirk, AbhiRiksh, Sjmatts and Anonymous: 59

8.2 Images

- **File:Beam_Split_and_fuse.svg** *Source:* https://upload.wikimedia.org/wikipedia/commons/f/ff/Beam_Split_and_fuse.svg *License:* CC BY 3.0 *Contributors:* Own work *Original artist:* Patrick Edwin Moran
- **File:Detector0RawResults.svg** *Source:* https://upload.wikimedia.org/wikipedia/commons/c/c8/Detector0RawResults.svg *License:* CC BY-SA 3.0 *Contributors:* Own work *Original artist:* Patrick Edwin Moran
- **File:KimDelayedChoiceQuantumEraserGraphsGIF.gif** *Source:* https://upload.wikimedia.org/wikipedia/commons/8/8c/KimDelayedChoiceQuantumEraserGraphsGIF.gif *License:* CC BY-SA 3.0 *Contributors:* Own work *Original artist:* Stigmatella aurantiaca
- **File:KimDelayedChoiceQuantumEraserGraphsSVG.svg** *Source:* https://upload.wikimedia.org/wikipedia/commons/f/f1/KimDelayedChoiceQuantumEraserGraphsSVG.svg *License:* CC BY-SA 3.0 *Contributors:* Own work *Original artist:* Patrick Edwin Moran
- **File:Kim_EtAl_Quantum_Eraser.svg** *Source:* https://upload.wikimedia.org/wikipedia/commons/2/21/Kim_EtAl_Quantum_Eraser.svg *License:* GFDL *Contributors:* Own work *Original artist:* Patrick Edwin Moran
- **File:Wiki_letter_w_cropped.svg** *Source:* https://upload.wikimedia.org/wikipedia/commons/1/1c/Wiki_letter_w_cropped.svg *License:* CC-BY-SA-3.0 *Contributors:* This file was derived from Wiki letter w.svg:
  Original artist: Derivative work by Thumperward

8.3 Content license