Quantum Erasure

In quantum mechanics, there are two sides to every story, but only one can be seen at a time. Experiments show that "erasing" one allows the other to appear

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In 1801, an English gentleman scholar named Thomas Young performed one of the most celebrated experiments in the history of physics. Here is how he described it two years later, in a lecture for the Royal Society of London:

> I made a small hole in a window shutter, and covered it with a thick piece of paper, which I perforated with a fine needle.... I brought into the sunbeam a slip of card, about one thirtieth of an inch in breadth, and observed its shadow, either on the wall, or on other cards held at different distances.

What Young saw on the opposite wall was not, as one might guess, a single thin shadow, but instead a whole row of equally spaced light and dark stripes or *fringes*, with the central band always bright. When he blocked the light on one side of the card, the fringes went away. He concluded that light from *both* sides of the card was required to make the pattern. But how could two rays of light combine to make a dark fringe? And why was the center of the shadow always bright, instead of dark? This was hard to fathom if light was made of particles that traveled always in straight rays, an idea that was shared by many physicists, including Isaac Newton.

With his "slip of card," Young set off a revolution in physics whose ripples are still being felt today. His experiment is now a staple of freshman physics laboratories, though it is now typically performed with two slits etched into a piece of opaque microfilm. (Thus the name, "Young's double-slit experiment.") The phenomenon he had observed, called *interference*, can be demonstrated easily enough with waves in a tank of water. Thus, by analogy, Young's experiment seemed to prove that light is made up of waves, as Dutch physicist Christiaan Huygens had advocated. But that was not the end of the story.

In the early 1900s, physicists discovered that light does behave in some ways as if composed of particles. In particular, there is a smallest "quantum" of light, called a photon. In 1909, Cambridge physicist Geoffrey Taylor repeated an experiment similar to Young's, which showed that individual photons suffer another interference phenomenon, called *diffraction*. By dimming the light until only one photon at a time reached the screen, he eliminated any possibility that the photons could interfere with one other. Yet after recording the results of many photons, Taylor found the same pattern of diffraction fringes. Apparently, then, an individual photon could "interfere with itself."

And it wasn't just photons. Other objects that seemed indisputably "particle-like," such as electrons, neutrons and even molecules of carbon-60, the buckyball, have subsequently demonstrated the same wavelike behavior. The self-interference of individual particles is the greatest mystery in quantum physics; in fact, Nobel Prize laureate Richard Feynman pronounced it "the *only* mystery" in quantum theory.

Recently, physicists have started to shed some light on this mystery through the demonstration of quantum erasers—in which one can actually choose to turn the interference fringes on or off. Our group has constructed a quantum eraser using a more elaborate version of Young's experiment and used it to demonstrate, in principle, the idea of "delayed choice," in which the experimenter can make the decision *after the particle has been detected*. The delayed-choice experiment almost sounds like altering the past. Lest any readers get ideas of building a "wayback machine," we will explain why quantum erasers don't really change history. But we do believe that they clarify how interference phenomena arise in quantum mechanics.

The Quantum Coin Toss

The appearance of interference fringes in the classical double-slit experiment is well understood. According to the wave theory of light, when two beams of coherent light with the same wavelength encounter each other, they combine. The most extreme situations are constructive interference, in which the waves reinforce each other, or destructive interference, in which they cancel each other out completely.

In Young's experiment, the paths from each slit to a given observation point are not necessarily equal in length. When they are equal—that is, when the observation point is centrally located between the slits—the waves arrive in phase and interfere constructively. That explains why Young always saw a light band in the center of his card's "shadow." On either side of this central band lies a region where one wave has to travel exactly half a wavelength farther than the other. There the waves interfere destructively and a dark band appears. Next comes

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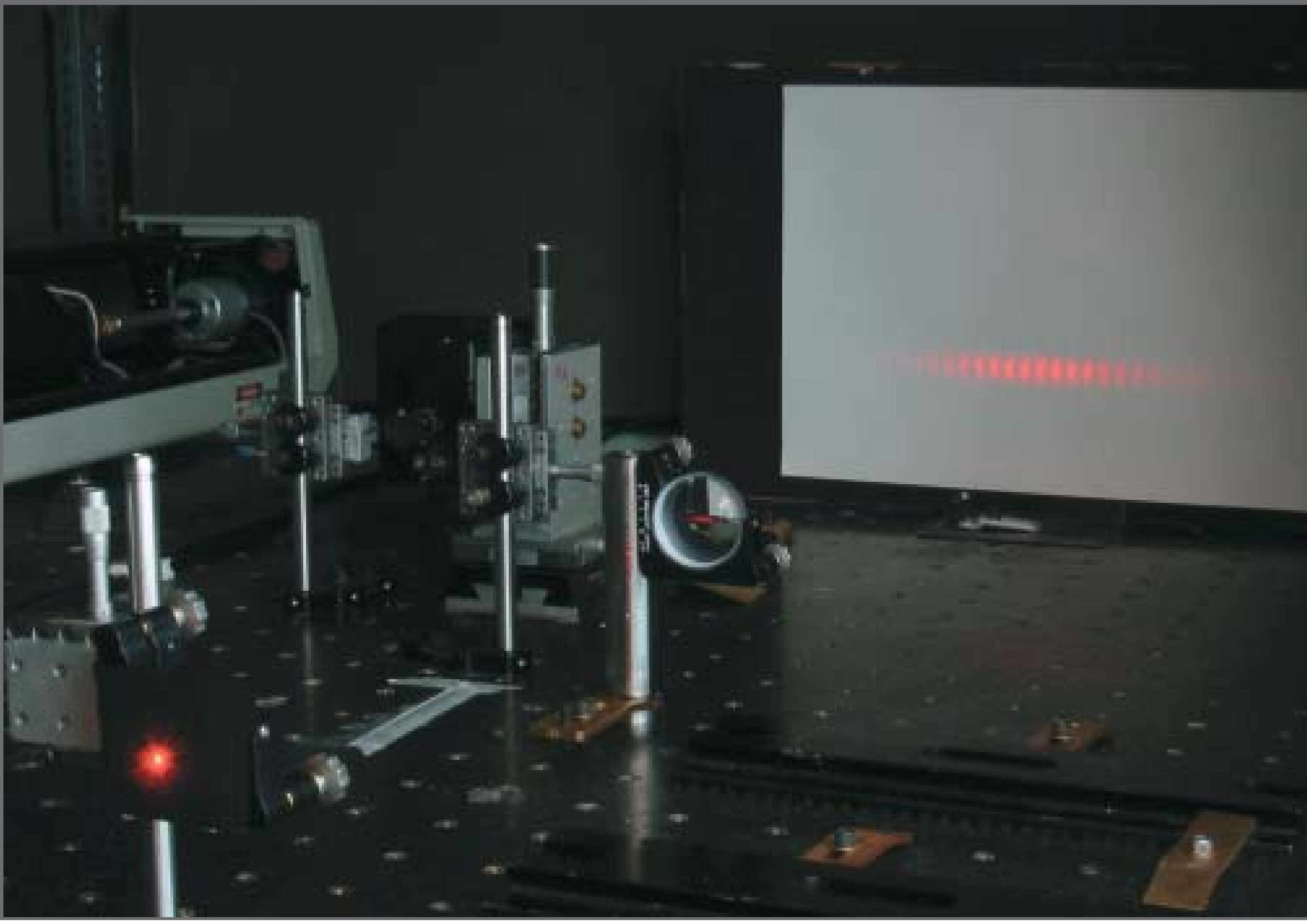

Figure 1. In a modern version of Thomas Young's double-slit experiment, a helium-neon laser illuminates a piece of microfilm, into which two slits are etched 0.1 millimeter apart. Next, the laser beam passes through a divergent lens *(center)*, which spreads it out so that the interference fringes produced by the double slits can be seen more readily on the screen at the back. Young's 1801 experiment used much more humble equipment: sunlight, a pinhole to make the light coherent, a card to split the beam and no divergent lens. Even so, he was able to discern at least five bright bands on the far wall. (Photograph courtesy of the authors.)

a region where one wave travels exactly one wavelength farther than the other. Here there is once again constructive interference and a band of light.

To understand why quantum interference is unexpected, it may help to draw an analogy to a coin toss. If it is a fair coin, the probability of getting heads is 50 percent and the probability of getting tails is also 50 percent. The probability of getting heads *or* tails is the sum of the individual probabilities:

$$\text{Prob (heads or tails)} = \text{Prob (heads)} + \text{Prob (tails)} = 100 \text{ percent}$$

Now consider a quantum "coin toss" based on Young's experiment. We send a beam of light at the double-slit apparatus, and put a photodetector a certain distance away on the other side. To dramatize the paradox, we place it in the middle of a dark interference fringe. Now, we turn down the light so that only one photon at a time passes through the slits. First we cover up slit 2, and we find, say, that 5 percent of the photons pass through slit 1 and trigger the detector. So Prob (slit 1) = 5 percent. Next we block slit 1 and find that 5 percent of the photons pass through slit 2 and trigger the detector: Prob (slit 2) = 5 percent. Now when we uncover both slits, creating two possible routes, we would expect to detect 10 percent of the photons. But no! Because we placed the detector in a dark fringe, we can run the experiment for hours and not see a single photon. That is,

$$\text{Prob (1 or 2)} = 0 \text{ percent} \neq \text{Prob (1)} + \text{Prob (2)}$$

The mind-bending explanation that quantum physicists have found for this behavior is the principle of *superposition*, which says that wavelike events combine according to a *probability amplitude* rather than a probability. Mathematically, a probability amplitude is a complex number (that is, a number like $0.1 + 0.2i$, where i denotes the square root of –1), not a positive real number. Thus two nonzero probability amplitudes (say, $0.1 + 0.2i$ and $-0.1 - 0.2i$) can add to zero, which is never true of classical probabilities.

Philosophically, the meaning of probability amplitudes is still a great mystery. Clearly, though, a "quantum coin" does not work the same way as a classical coin. Thanks to the superposition principle, a photon, our "quantum coin," can give a combination of both heads and tails.

Matter Waves Matter

If all of this sounds pretty unbelievable to you, then you are in good company. Even the originators of quantum physics struggled with its concepts, and some of them never accepted the theories they were forced into. The German physicist Max Planck, who, in 1900, was the first to propose that light behaved as if it were made up of quanta, envisioned this only as some sort of

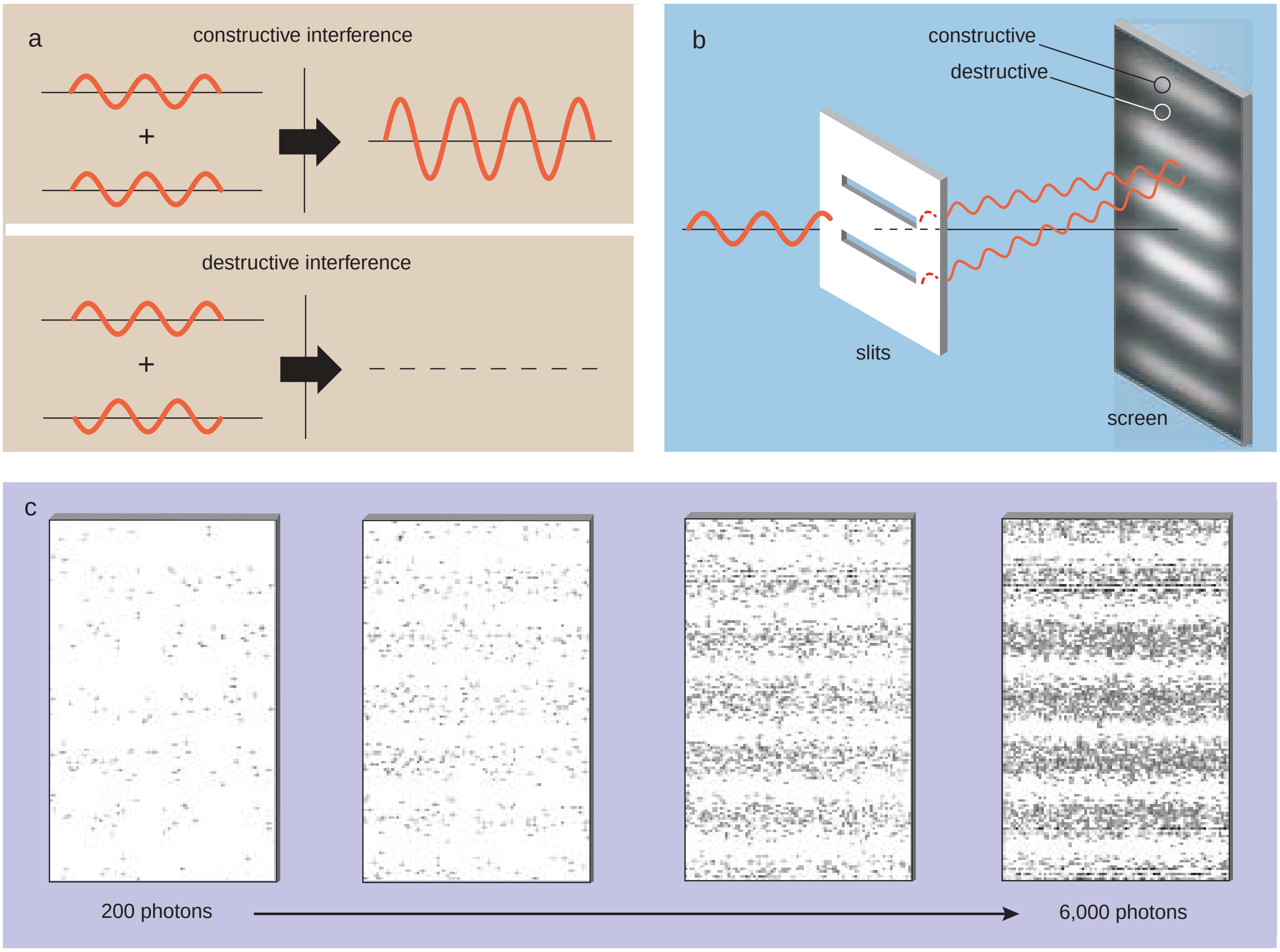

Figure 2. Physicists normally explain Young's interference fringes with the wave theory of light *(a)*. Two light waves reinforce each other constructively, creating a brighter beam when they are in phase, and reinforce each other destructively when they are out of phase *(b)*. After light waves pass through the two slits, they will interfere constructively wherever one wave travels a whole number (0, 1, 2, …) of wavelengths farther than the other. They interfere destructively when one wave travels a fraction (1/2, 3/2, 5/2, …) of wavelengths farther. According to the geometry, this results in a series of equally spaced light and dark bands, called interference fringes *(c)*. Modern versions of Young's experiment make it possible to send one photon at a time through the slit apparatus. As this computer simulation shows, the interference pattern emerges unambiguously as the number of photons increases. Though none of the photons interfere with each other, somehow they continue to produce interference fringes. The only explanation seems to be that a photon can pass through both fringes simultaneously and interfere with itself.

mathematical trick that happened to fit the experimental data. Unlike Planck, Albert Einstein accepted the idea of quanta of light, but had misgivings over the later developments of quantum theory. He could not come to terms with the idea that what we observe and consequently call "reality" seems to be random. (Quantum mechanics deals with probabilities and therefore does not say anything about where the photon *is*; only where it is *likely* or *unlikely* to turn up.) Einstein was bothered also by the implication that this reality exists in a unique, unambiguous state only when we are observing. He expressed his discontent to Abraham Pais: "Do you believe that the moon exists only when you look at it?" Interestingly, it was Einstein's dissatisfaction that motivated and still motivates much of the modern research in quantum mechanics.

In the late 1920s, Danish physicist Niels Bohr formulated an interpretation of quantum mechanics known as the "Copenhagen interpretation" (see "Science as Theater," *American Scientist*, November–December 2002) that is the most widely accepted way of dodging the paradoxes of quantum physics. In particular, Bohr's complementarity principle states that for a pair of complementary variables or "observables," such as position and momentum, the precise knowledge of one prevents any knowledge of the other. Position is a "particle-like" observable: A particle has a specific location in space, but a wave does not. Somewhat less obviously, momentum is a wavelike observable. In 1927, Louis de Broglie proposed that when a particle, such as an electron, acquires momentum it also acquires a characteristic wavelength. According to Bohr, every quantum object is *both* wave and particle, and the behavior we observe is determined simply by the kind of measurement we choose to make. If we measure a particle-like property, then the object will exhibit particle-like behavior. Later, if we choose to measure a wavelike property, we will see the object act as a wave. But we cannot do both at once.

On several occasions, Einstein thought he could poke holes in the Copenhagen interpretation. One such criticism was a "thought experiment" (never performed in a laboratory) in which a double slit is suspended by sensitive springs so that it is free to move back and forth. When a photon is scattered by the spring-loaded slits, it gives the apparatus a slight kick. By noting the recoil of the apparatus together with the position at which the photon is later detected, the experimenter could discover through which slit the photon "passed" (a position measurement). At the same time, Einstein argued, the recoil measurement, made after the photon has passed, would not alter its trajectory, so the interference fringes would still be observed. From the separation of the fringes, the wavelength—a wavelike property—could be inferred. Thus both the momentum and the trajectory would be known, and the complementarity principle must be a hoax!

However, Bohr showed that Einstein's argument had a flaw. To do so, he invoked another principle of quantum mechanics: Heisenberg's uncertainty principle. In spite of its vague-sounding name, this principle is a very quantitative statement about the best precision with which one can measure complementary variables. The recoil of the double-slit apparatus necessarily disturbs the system, and creates an uncertainty in the detection of the photon's position on the detection screen. This uncertainty is just enough to blur the interference fringes, so that the momentum can no longer be measured.

For many years it was thought that Heisenberg's principle was the mechanism responsible for enforcing complementarity. However, it was recently hypothesized that complementarity is more fundamental—that it should be possible to "mark" a particle's position in a way that does not alter its momentum. This leads to a class of experiments known as quantum erasers.

Which Path?

Roughly 20 years ago, physicists Marlan O. Scully and Kai Drühl, then of the Max Planck Institute for Quantum Optics in Garching, Germany, and the University of New Mexico, shook the physics community with the idea of quantum erasure. Their logic was as follows: If the information providing the object's trajectory can be determined without significantly perturbing it, then the interference should disappear (in accordance with complementarity). But if that information is subsequently "erased," then the interference should return. One might even say that "interference equals ignorance" (of the particle's path).

Later, Scully joined with Berthold-Georg Englert and Herbert Walther, also of the Max Planck Institute, in proposing a way to bring this about. In their proposal, the interfering object is an atom with electrons excited to a very high energy level. Behind each of the slits is a microwave cavity designed to capture a photon emitted by the atom as it decays to a less excited state. Simply by looking to see which cavity contains the photon, the experimenter could tell which slit the atom passed through. Complementarity implies that the interference fringes would have to disappear. But if the experimenter took out the wall between the two cavities,

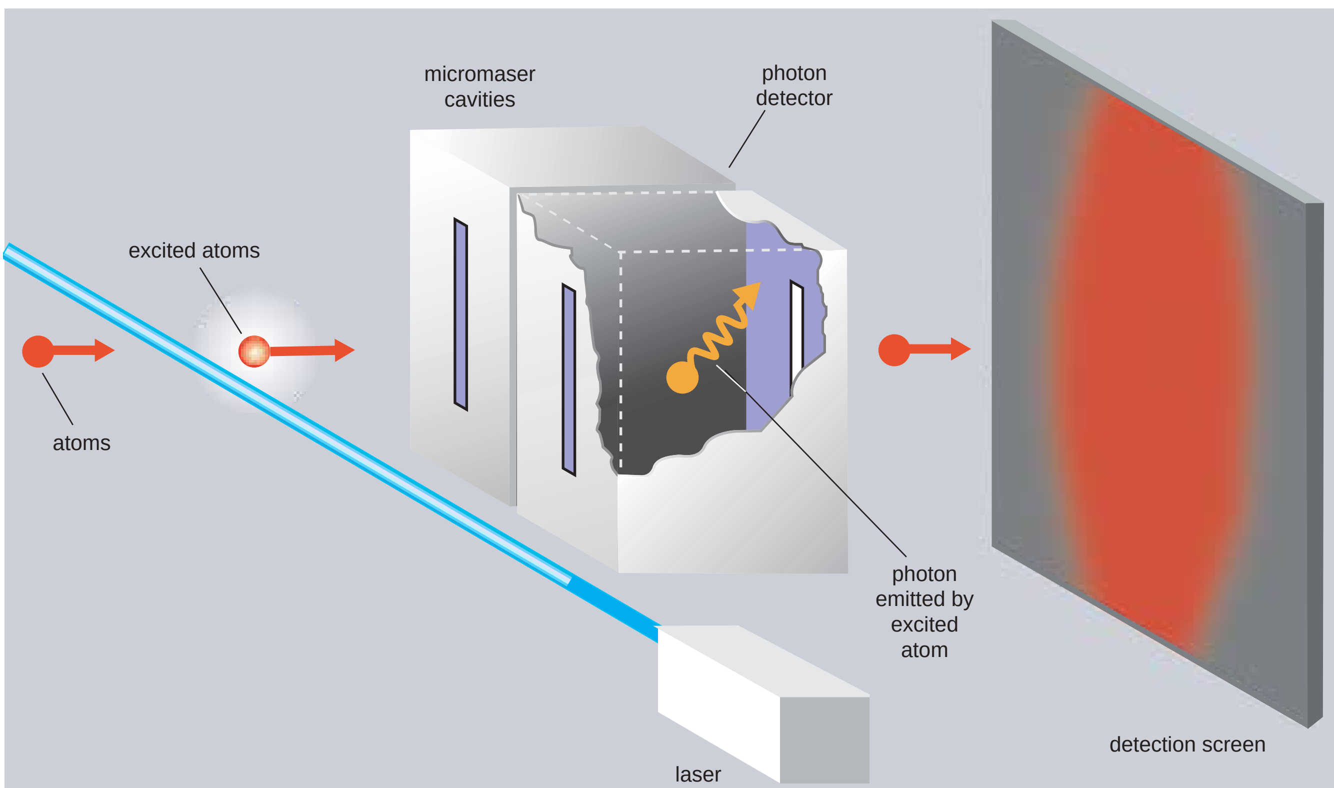

Figure 3. "Quantum eraser" thought experiment by Scully, Englert and Walther eliminates interference (a wavelike property) by recording information on which slit an excited atom went through (a particle-like property). An atom is excited to a high energy state by a laser. It then passes into the double-slit apparatus. Behind the slits are two microwave cavities that are sufficiently long for the atom to drop out of its excited state before it exits the cavity. This releases a photon, enabling the experimenter to detect which slit the atom passed through. According to Bohr's complementarity principle, it cannot then act like a wave. Therefore, multiple repetitions of the experiment will produce a large blob on the detection screen instead of interference fringes. But removing the wall between the cavities would erase the "which-path" information, and interference would be restored.

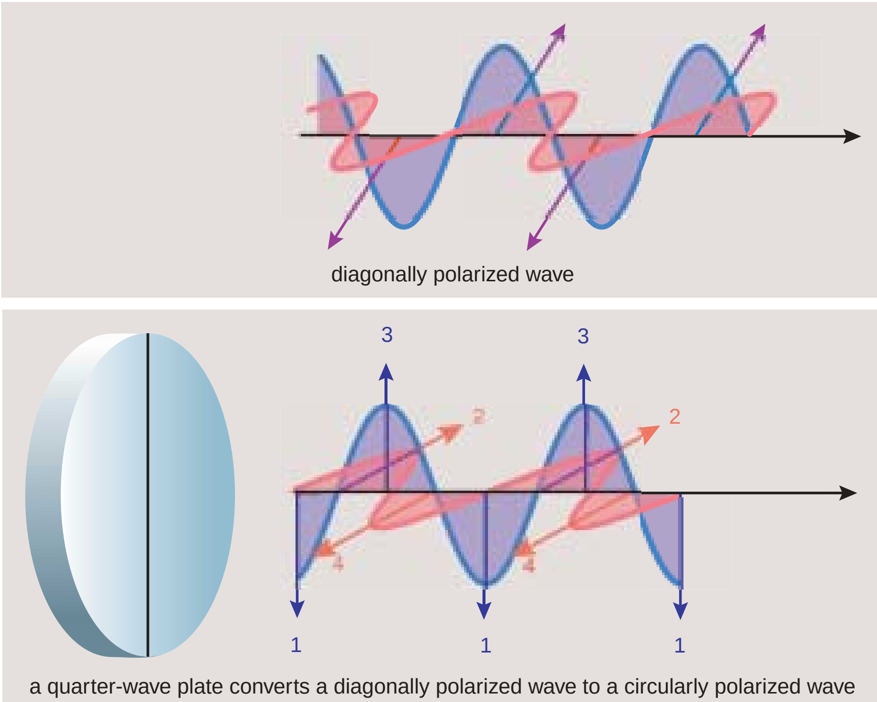

Figure 4. Our version of quantum erasure uses polarization as a marker for which slit a photon passes through. A linearly polarized light wave *(top)* consists of alternating electric and magnetic fields. Here only the electric field is shown. Because it has equal horizontal and vertical components, it is said to be diagonally polarized *(top, purple arrows)*. A quarter-wave plate, which the authors use in their experiments, retards one component *(bottom figure)*. This causes the net electric field to rotate as it propagates through space *(bottom, arrows 1, 2, 3, 4)*. Because the rotation is counterclockwise to a viewer looking at the incoming wave, this is called a left-circularly polarized wave. Retarding the other component would have created a right-circularly polarized wave. With its axis vertical, the quarter-wave plate turns diagonally polarized light into circularly polarized light, and with the axis at 45 degrees, it turns vertically polarized light into circularly polarized light.

the extra "which-path" information would be erased, and—presto!—the fringes should reappear.

So far no one has succeeded in performing the Scully-Englert-Walther experiment. However, we have performed an analogous experiment using photons, which is much easier to implement.

Our experiment uses polarization as a path marker. Any electromagnetic wave, such as light, has a polarization determined by the oscillations of the electric and magnetic fields that make up the wave. *(See Figure 4.)* These fields always oscillate in a plane perpendicular to the direction of propagation, but they can point in various directions within this plane: for example, vertically, horizontally, or at an angle of 45 degrees or –45 degrees to the horizontal. They can even rotate as they propagate forward, so that the light wave turns like a right-handed screw or its mirror image, a left-handed screw. Such waves are said to be (right- or left-) circularly polarized. Optical components called *wave plates* can be used to change the direction of polarization, or to change a linearly polarized beam into a circularly polarized one. Another common optical component is a *polarizer*, which allows only light with a given polarization to pass. When a circularly polarized beam passes through a horizontal polarizer, the vertical part of the wave is stripped away and all that remains is a horizontally polarized beam, half as intense as the original.

Now imagine that we repeat Young's experiment with many horizontally polarized photons. Behind the slits we insert two quarter-wave plates, one that turns the horizontally polarized photons into right-circularly polarized photons, and the other that makes them left-circularly polarized. Remarkably, the interference fringes will disappear and be replaced with a single swath of light, most intense in the middle. If we plot the distribution of photons on a graph we get a bell-shaped curve.

What happened to the interference? The photons no longer seem to behave like quantum coins but instead like boring, classical ones. The wave plates have now unambiguously correlated each slit with a particular polarization. Using a circular polarizer, we could measure the polarization and discover which slit each photon passed through. Note that we don't actually have to measure the polarization to destroy the interference pattern. It is enough that the which-path information is *available* to us; playing dumb will not restore the interference.

An Entangled Story

To demonstrate quantum erasure, one must do more than find a way to mark which path the photon took; one must also show how to "erase" that information. We do this by inserting a linear horizontal polarizer between the quarter-wave plates and the detector. When we put the polarizer into place and repeat the experiment, instead of the bell-shaped curve of photon detections, we see an interference pattern. It's as if we put on a pair of sunglasses and suddenly saw everything around us in stripes.

But how can that be? We have already said that simply playing dumb does not bring back interference. Why does a horizontal polarizer bring it back? The answer is that it erases the which-path information. Remember that our horizontal polarizer filters either a right-circular or left-circular polarized photon into a horizontally polarized one, so that there is no longer any way to tell the difference between them. So once a photon has passed through the polarizer, it cannot be determined whether it came from slit 1 or slit 2. With the particle-like information removed, the photons are free to start acting like waves again.

Similarly, if we place a linear vertical polarizer between the quarter-wave plates and the detector, we again erase the which-path information. However, in this case we observe a fringe pattern —commonly called anti-fringes—that is exactly out of phase with the pattern we saw through the horizontal polarizer. Anti-fringes exhibit a central minimum (dark stripe).

We now have two ways of dividing the experimental results into subsets. With a circular polarizer, we could separate the photons into two groups: those that passed through slit 1 (right-circular) and those that passed through slit 2 (left-circular). With a linear polarizer, we can separate them into two different groups: those that give a fringe pattern (horizontal) and those that give an antifringe pattern (vertical). This is the essence of quantum erasure.

Does the uncertainty principle say anything about this experiment? No. Polarization and position are not complementary variables, so, as in the Scully-Englert-Walther proposal, Heisenberg's uncertainty principle does not apply here. So what is enforcing the complementarity principle?

The answer is *quantum entanglement*. When a photon passes through the double-slit apparatus, it enters a superposition of position states: slit 1 + slit 2. The quarter-wave plates perform an additional conditional logic operation. If the photon passes through slit 1, it emerges with right-circular polarization and if it passes through slit 2, it emerges with left-circular polarization. Thus the polarization has become *entangled* with the path. The photon's state can be described as a new and more complicated superposition:

(slit 1 AND right-polarized) +
(slit 2 AND left-polarized)

Because the two observables are now entangled, manipulating the information about either one automatically changes information about the other. It is completely equivalent to describe the photon's state as:

(fringes AND horizontal-polarized) +
(anti-fringes AND vertical-polarized)

To return to the coin-toss analogy, the position and polarization observables are now like two "telepathic" coins. Coin 1 lands heads half the time and so does coin 2, so if you look at either one in isolation it appears completely normal. Their quantum strangeness only emerges when you start flipping them, and discover that every time coin 1 lands heads, coin 2 does too!

Telepathic coins may seem pretty weird. They did to Einstein, too; in a famous 1935 paper with Boris Podolsky and Nathan Rosen, he argued that they would violate the complementarity principle. Nevertheless, quantum entanglement is very much a reality. Physicists are now experimenting, both theoretically and in the laboratory, with ways to use entanglement in quantum computers and unbreakable cryptosystems.

Changing History?

Our last variation on Young's experiment incorporates quantum entanglement in a much more overt way, to produce a seemingly paradoxical situation known as delayed choice, originally proposed by John A. Wheeler. Even spookier than telepathic coins, delayed choice seems to open up the possibility of changing the past. But we emphasize the word "seems"—in reality it does nothing of the sort.

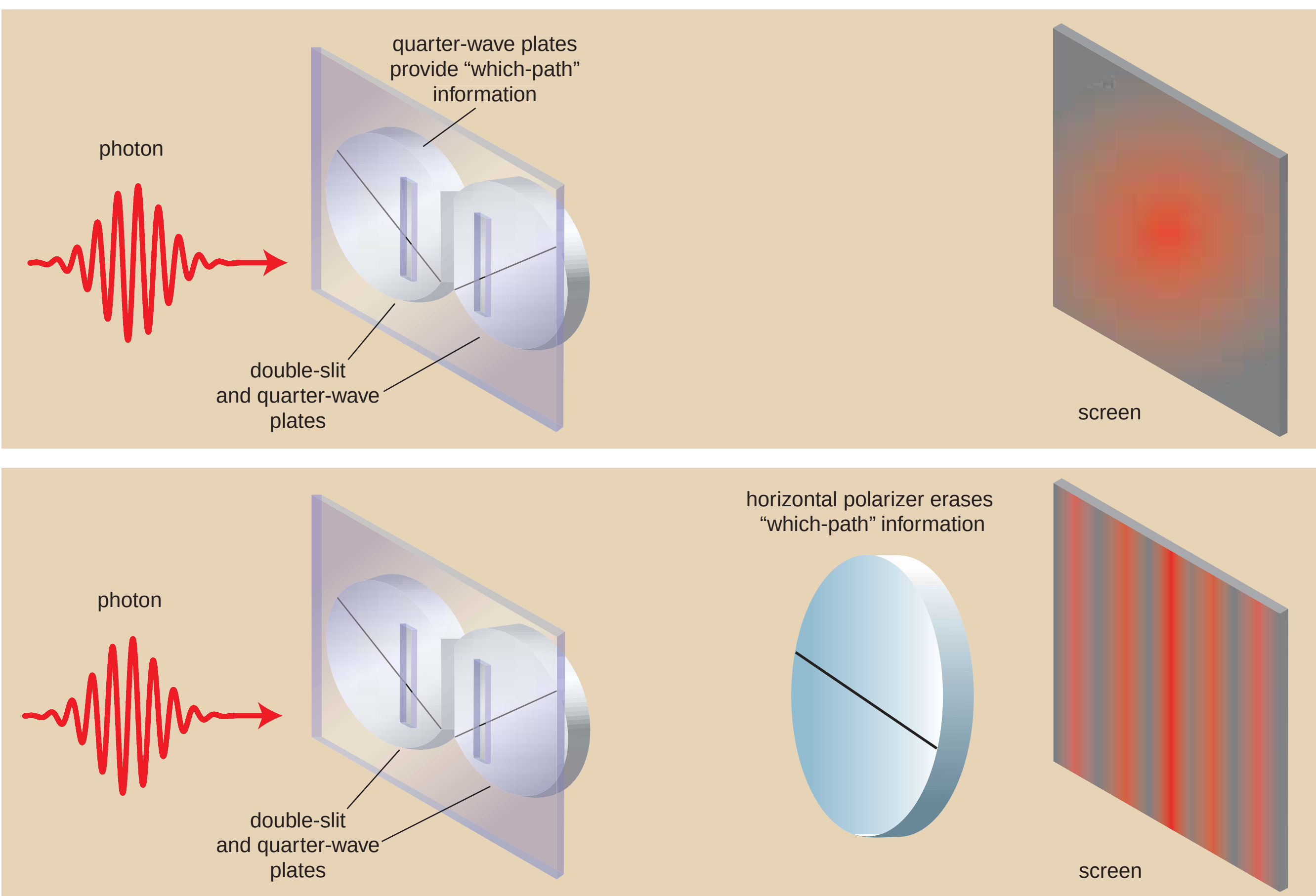

Figure 5. In the authors' version of quantum erasure, quarter-wave plates are placed behind the slits, converting the photons to left-circular and right-circular polarizations respectively. This makes "which-path" information available to the experimenter, and the interference fringes disappear *(top)*. However, a horizontal polarizer *(bottom)* converts either of the circular polarizations to horizontal polarizations so there is now no longer any way to distinguish between photons that went through the top and bottom slits. "Which-path" information is erased, and—as the authors have demonstrated in the laboratory—the interference fringes return.

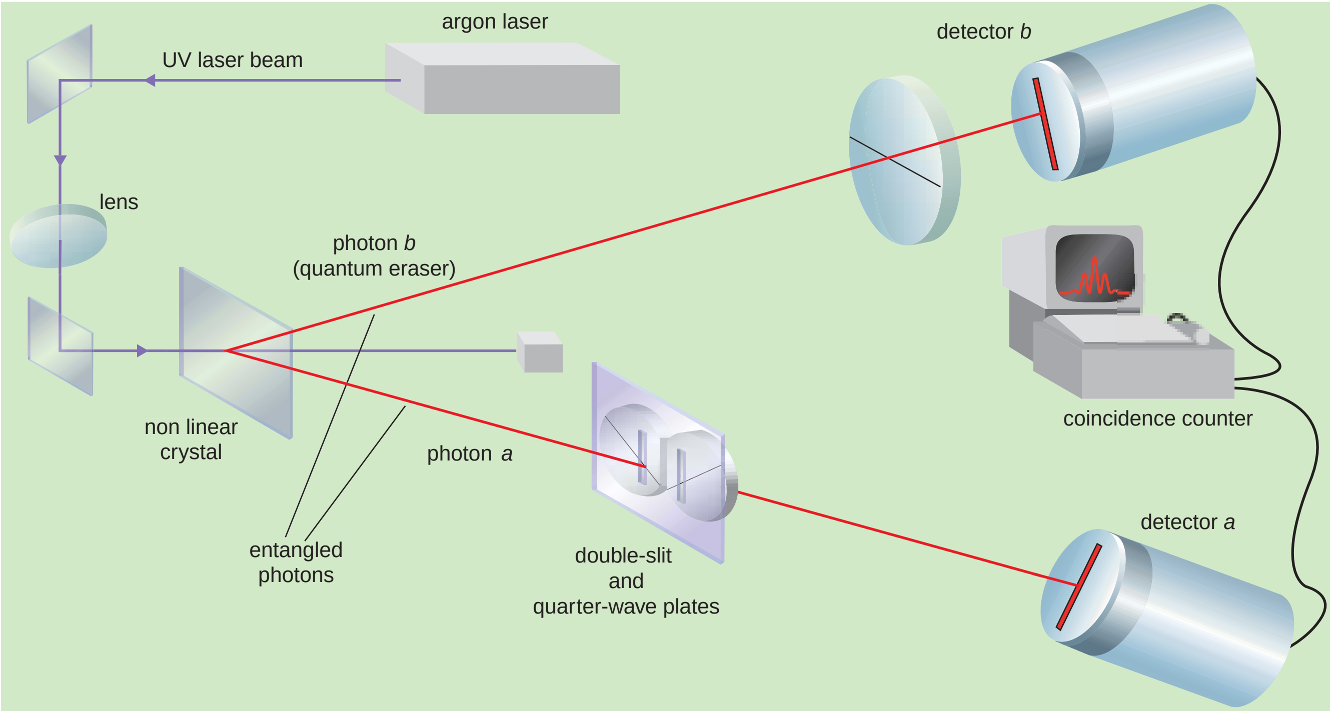

Figure 6. In "delayed-choice" experiment, a second photon is used as the quantum eraser. Photons *a* and *b* are prepared in an entangled state, so that any measurement of the polarization of *b* immediately determines the polarization of *a*. After photon *a* passes through the slit apparatus, the polarization of *b* is entangled with the "which-path" information for photon *a*. Coincidence detection allows the experimenter to determine which photons are entangled with one another. If both detectors light up within a nanosecond of each other, then the two photons are almost certainly an entangled pair.

In the delayed-choice experiment, we create a pair of entangled photons, which we will call *a* and *b*, in such a way that whenever photon *a* is observed to have horizontal polarization, photon *b* will necessarily be vertically polarized, and vice versa. (We do this by a nonlinear optical process called "spontaneous parametric down-conversion," in which we shine an ultraviolet argon laser onto a thin crystal, which emits two "twin" photons.) We maneuver photon *a* so that it passes through the double slit and the quarter-wave plates and then on to a detector, while *b* goes directly to a separate polarization detector. This time the polarization of photon *b* will be our quantum eraser controller.

Because *a* and *b* are entangled, any measurement of *b* tells us something about *a*. We can choose either to make a measurement on *b* that provides which-path information for *a*, or we can make a measurement that preserves interference. If we measure the horizontal or vertical polarization of *b*, we preserve the which-path information. (This is true because, for example, "*a* right-circular AND *b* horizontal" means that photon *a* went through slit 1, while "*a* left-circular AND *b* horizontal" means it passed through slit 2.) To erase the which-path information for *a*, we can measure instead the *diagonal* polarization of *b*. A measurement of the positive diagonal direction (45 degrees) will give interference fringes on *a*'s detection screen, while a measurement in the negative diagonal direction (–45 degrees) will produce anti-fringes.

In our laboratory, we have demonstrated that the quantum eraser effect occurs regardless of the order *a* and *b* are detected in. Because our detector for photon *b* is not very far away (1.5 meters), the delay in detection between *a* and *b* is minuscule—about 5 nanoseconds. But there is no reason in principle why we couldn't send *b* very far away—say, out to Mars. This would give the observer on Mars several minutes to decide whether we, back on Earth, will observe fringes or no fringes. But what if we have already collected our data and observed the opposite thing?

In fact, this cannot happen. The delayed measurement on Mars doesn't change any events on Earth—it only changes our bookkeeping. Here is the explanation, in the form of an imaginary dialogue. Suppose Alice sets up a double-slit experiment with quarter-wave plates on Earth. Her friend Bob, who lives on Mars, sends her a box of photons. Alice sends each photon through the double-slit apparatus and then measures its position: "Photon 567 was detected at position $x = 4.3$." Little does she know that Bob, on Mars, has kept an entangled twin of each photon. For each twin he chooses to measure the polarization, either in the horizontal and vertical directions or in the +45 degrees and –45 degrees diagonal directions. He writes the results down in his lab book, "Photon 567(B) was detected with horizontal polarization." A few weeks later, Bob pays Alice a visit.

Alice: Hi Bob! How's Mars? Look, I did that double slit and quarter-wave plate experiment that those physicists wrote about. Just as they said, I got a boring bell-shaped curve, with no interference at all.

Bob: (*a prankster*) Are you sure? Here, go back to your data and plot the positions of just these photons. (*He hands Alice a list of the photons for which he measured +45 degrees polarization*.)

Alice: Wow! Interference fringes! How did you make the photons interfere after they were already recorded in my lab book?

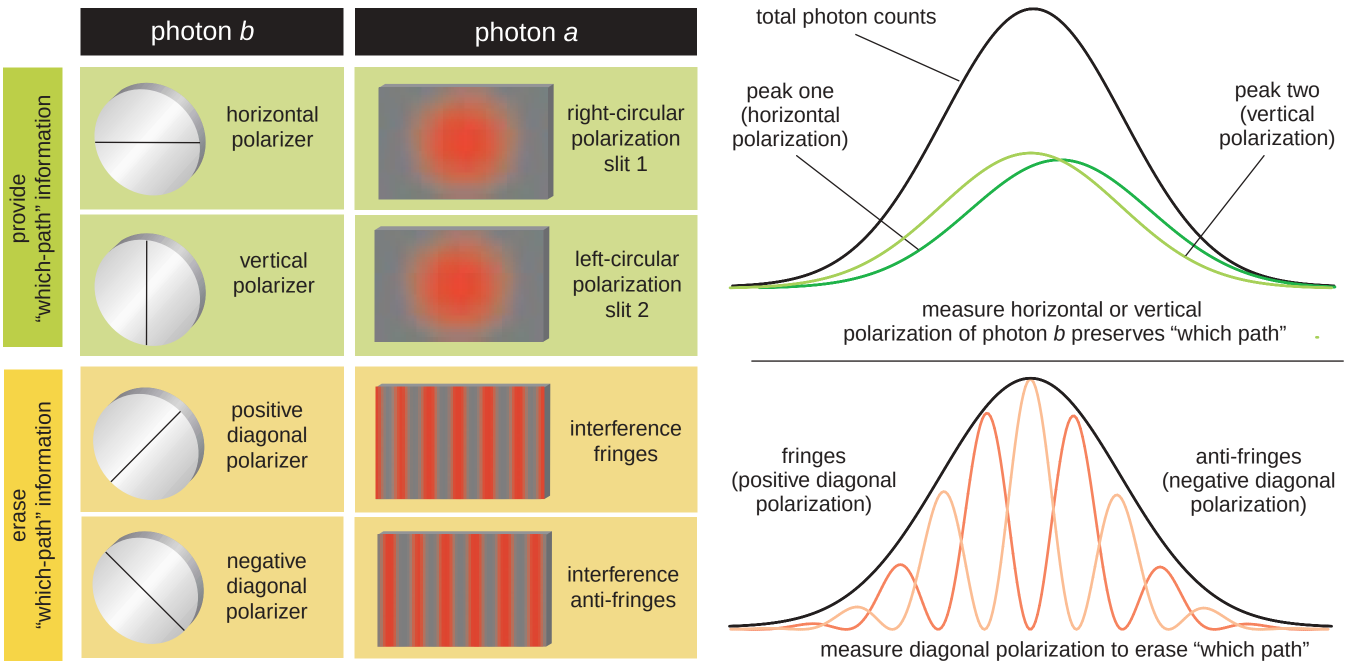

Figure 7. "Delayed-choice" paradox *(see Figure 6)* amounts to a change in bookkeeping, not a change in history. The behavior of a pair of entangled photons *(a* and *b)* can be recorded independently by two observers. Observer A repeats the experiment many times and plots a graph showing where the photons are detected. Regardless of which kind of measurement observer B chooses, observer *A*'s graph will be a bell-shaped curve. (This corresponds to the "blob" seen in *Figure 5.)* If observer *B* chooses to measure horizontal/vertical polarization, each of his *b* photons will retain "which-path" information for their entangled twins. Thus the *a* photons that *A* has measured will separate into two groups, one that passed through slit 1 and one that passed through slit 2. The photon counts for each of these groups will produce bell-shaped curves, slightly displaced from one another *(upper right, green lines)*. If observer *B* chooses to measure diagonal polarization, the "which-path" information will be erased. In that case, the entangled photons that *A* has measured can be separated into two different groups, one forming interference fringes and the other forming anti-fringes *(bottom)*.

Bob: You think that's cool? Check this out. (*Now he hands Alice a list of the photons he measured with vertical polarization.*)

Alice: No fringes! It's back to a bell-shaped curve again. (*Bob hands her a list of the photons with –45 degrees polarization and she plots their positions.*) Now the interference is back, but this time anti-fringes. Bob, this is amazing. You have control over the past. Can you go back and change my exam grades?

Bob: I'm sorry, Alice, but there is no magic here. The photons I gave you were actually entangled with photons I kept for myself. I did polarization measurements on them, and that is where these mysterious lists of photons came from. But my measurements didn't change history. All they told me was how to divide up your experimental results. I can either divide them into fringes and anti-fringes, or I can divide them into two bell-shaped curves. But I can't change where any individual photon actually landed.

Alice: Rats. I *really* needed that A in physics. (*Brightens.*) But hey! Maybe we can make this into a scheme for sending secret messages!

Bob: Believe me Alice, somebody is already working on that.

Conclusion

Presumably, Einstein would not be happy with these experiments. Quantum erasure seems to confirm that the complementarity principle is indeed a fundamental part of quantum theory. Although such experiments have done much to illustrate the dual nature of quantum objects, physicists are still unable to explain *why* wave-particle duality exists. In this respect, we would still agree with Richard Feynman, who wrote in the 1960s, "We cannot make the mystery go away by explaining how it works. We will just tell you how it works."

Even so, we are making progress. We understand now that quantum entanglement, a necessary part of the act of measurement itself, rather than the "quantum uncertainty" involved in the measurement, is responsible for complementarity in the double-slit experiment. This may seem like a subtle point, but it will make many physicists sleep more soundly at night.

Bibliography

Feynman, R. P., R. B. Leighton and M. L. Sands. 1965. *The Feynman Lectures on Physics.* Reading, Mass.: Addison-Wesley.

Peres, A. 1995. *Quantum Theory: Concepts and Methods.* New York: Kluwer Academic Publishers.

Scully, M. O., B. G. Englert and H. Walther. 1991. Quantum optical tests of complementarity. *Nature* 351:111–116.

Scully, M. O., and M. S. Zubairy. 1997. *Quantum Optics.* New York: Cambridge University Press.

Walborn, S. P., M. O. Terra Cunha, S. Pádua and C. H. Monken. 2002. Double-slit quantum eraser. *Physical Review A* 65:033818.

Wheeler, J. A., and W. H. Zurek. 1983. *Quantum Theory and Measurement.* Princeton University Press.

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