# The Duality in Matter and Light

*In quantum mechanics, objects can behave as particles or as waves. Studies now emphasize that such complementary features are more fundamental than has generally been appreciated*

by Berthold-Georg Englert, Marlan O. Scully and Herbert Walther

In the microcosmos of quantum mechanics, phenomena abound that fly in the face of common sense. Many of these effects are a consequence of the principle of complementarity. Its most popular manifestation is the wave-particle duality. A microscopic object, such as a photon, an atom or an electron, can appear to behave as a water wave in one instance and as a discrete particle in another. Both features complement one another as a complete description of the object. Since the idea of complementarity was first enunciated more than 70 years ago, a belief common among many physicists has been that it is simply a consequence of the uncertainty relation. According to this rule, two complementary variables, such as position and momentum, cannot simultaneously be measured to less than a fundamental limit of accuracy. The uncertainty relation normally prevents one from learning everything about the behavior of a quantum object. As a result, we can never see the object acting both as a particle and as a wave.

Recently we and our colleagues have worked to show that uncertainty is not the only enforcer of complementarity. We devised and analyzed both real and thought experiments that bypass the uncertainty relation, in effect, to “trick” the quantum objects under study. Nevertheless, the results always reveal that nature safeguards itself against such intrusions—complementarity remains intact even when the uncertainty relation plays no role. We conclude that complementarity is deeper than has been appreciated: it is more general and more fundamental to quantum mechanics than is the uncertainty rule.

Wave and particle behaviors manifest themselves distinctly when tested. The wavelike aspect shows itself in interference patterns. Throw two stones at the same time into a quiet lake, and you will see how the emerging circular waves will eventually overlap. They reinforce one another where crest meets crest or extinguish one another where crest meets trough. The same effect appears if we shine light through two slits, which act as the two stones. The light wave travels through both slits, so that two smaller waves come out from each slit. These waves interfere, producing a series of light and dark fringes when projected onto a screen [*see illustration on page 88*]. The particlelike aspect, in contrast, always appears as photons, which are invariably seen as indivisible entities. Rather than registering a continuous intensity, a suitable detector counts a discrete number of photons.

A more impressive demonstration of particle and wave attributes takes place if we send photons through the slits one at a time. In this case, each photon produces a spot on the screen. But when we collect the results of many such events, an interference pattern emerges. (Specifically, the interference pattern represents the probability of the photon hitting one point or another.)

***Niels Bohr and Albert Einstein analyze the two-slit experiment.***

This counterintuitive dual nature of both wave and particle does not exhaust complementarity. Most quantum objects (a silver atom, say) have an internal structure that can result in magnetic properties. Measurements may find the “poles” of this “magnet” to point either up or down, or right or left. But we can never find the poles to point “up and left.” Thus, the property of being up or down is complementary to that of being left or right, quite analogous to wave versus particle behavior.

A more striking, or even mysterious, aspect of complementary features concerns their predictability. Suppose a measurement found that our microscopic magnet points up. We then perform a second experiment to decide whether the magnet points left or right. What we find is that there is nothing predictable about the outcome: left or right occurs with a probability of 50 percent each. Are we lacking some knowledge that would allow us to make a prediction? No, the case is more serious than that: the result of the left-right measurement cannot be known beforehand.

The reason for this ignorance is the principle of complementarity. It states that one cannot simultaneously know the values of two related (that is, complementary) variables, such as whether the magnets point left or right and up or down. In fact, absolutely precise information about one variable means that nothing can be known about the other. Textbooks often illustrate the law using the position and momentum of a moving particle as the two complementary properties. The more accurate the position measurement, the less accurate the momentum information, and vice versa. The precise numerical statement is Heisenberg’s uncertainty relation.

The principle of complementarity implies that in the microcosmos, complete knowledge of the future, in the sense of classical physics, is simply not available. If one of a pair of complementary properties of a quantum object is known for sure, then information about the second complementary property is lost.

In the two-slit setup, if we discover by any means whatsoever through which slit each one of the photons traveled (thus acquiring “which-way” information), we lose the interference pattern on the screen. The possession of which-way information means that at the slits the particlelike nature of the photons must be manifest, rather than the wavelike aspect necessary for interference fringes. We can have either which-way information or the interference pattern, but never both together. (Although we stated earlier that the particle nature is always recognized when the photons are detected on the screen, the information does not tell us anything about the state of affairs at the slits where the interference pattern originates.)

This complementarity is a fact of life, and we have to live with it. The Danish physicist Niels Bohr, more than anyone else, insisted on just that, and he deserves the lion’s share of the credit for making us accept complementarity as a fundamental truth. It did not come easily, and the resistance put up by devil’s advocates as prominent as Albert Einstein himself was formidable. The thrust of their arguments centered on whether complementary properties could be measured simultaneously. Here is an imaginary transcript of one of their many clarifying debates:

Bohr: I see you are once more sketching a two-slit experiment. What are you heading for this time?

Einstein: Just wait, Niels, until I have finished. Here you go [*see box on page 89*]. A plane light wave illuminates a plate that has two slits through which the light can reach a screen. Provided the geometry of the setup is right, an interference pattern appears on the screen—a series of light and dark bands.

B: That’s what we teach our students. What’s new?

E: Be patient, please. Before presenting the new thought, let me state the old affairs to make sure that we agree on those. You will not object to the statement that the interference pattern demonstrates the

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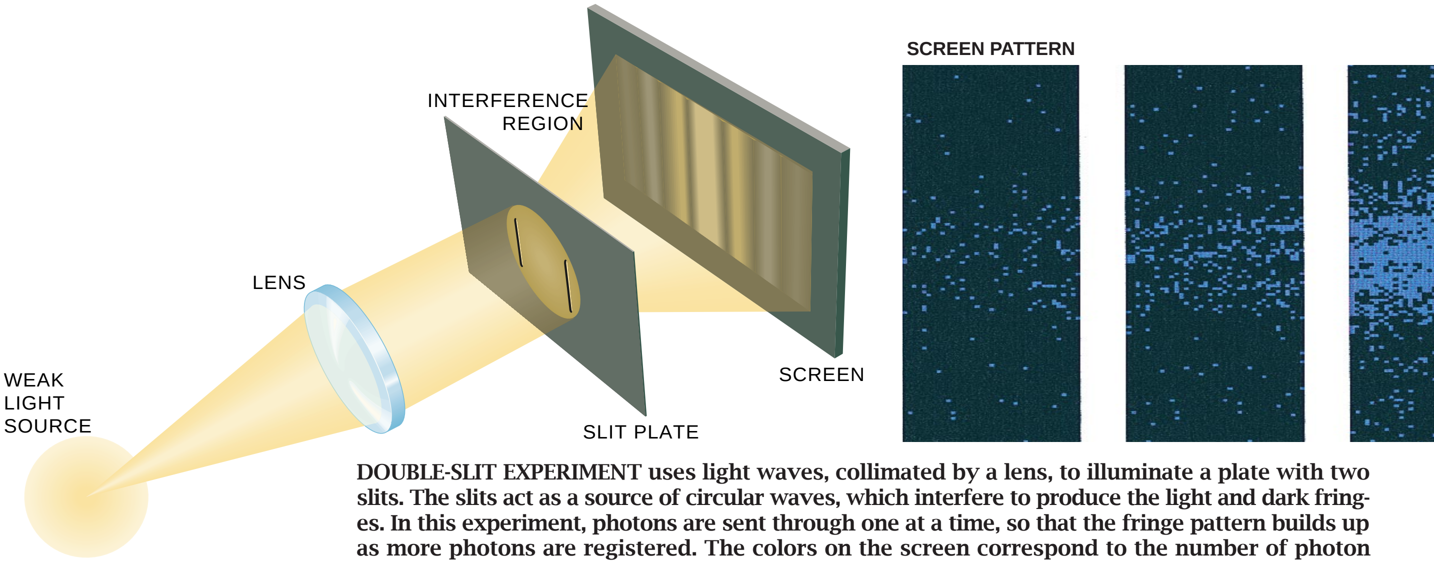


**DOUBLE-SLIT EXPERIMENT uses light waves, collimated by a lens, to illuminate a plate with two slits. The slits act as a source of circular waves, which interfere to produce the light and dark fringes. In this experiment, photons are sent through one at a time, so that the fringe pattern builds up as more photons are registered. The colors on the screen correspond to the number of photon**

wave nature of light?

B: Of course not.

E: You will also agree that what you call complementarity implies here that there is no way of knowing through which slit any one of the photons reached the screen to deliver its contribution to the interference pattern.

B: Quite right so.

E: Well, you know I always found it hard to believe that the Lord took recourse to throwing dice. Let me now come to the new twist. Contrary to what was just said, I can tell through which slit the photon came. Say we saw the photon hitting the screen at the site of the first side maximum—that is, one of the bright bands closest to the center of the pattern. To get there, the photon needed to be deflected by the slit it traversed through.

But as Isaac Newton taught us, there is no action without reaction. So when the slit plate gives a jolt to the photon, a corresponding jolt is delivered by the photon to the plate. And the strength of the jolt depends on the slit through which the photon went. By suspending the slit plate sensitively, I can in principle register its recoil. The amount tells me through which slit the photon came.

B: Aha. You would then have "which-way" information for each individual photon and in the same experiment observe an interference pattern.

E: Yes.

B: But that is inconsistent with complementarity.

E: Yes.

B: Nice try, but I'm afraid you overlooked something—namely, the quantum properties of the slit plate. I can explain the reasoning with mathematics [*see box on opposite page*]. But the gist of the matter is that in order to observe the interference pattern, the position of the slit plate must be fixed rather precisely.

E: Certainly, because otherwise the two-slit fringe pattern cannot build up, and we would observe the scatter pattern of a single slit.

B: Now to distinguish one path from the other, we must know the momentum of the recoiling slit rather precisely. In fact, I can show that the interference pattern appears only when the uncertainties in both the position of the slit plate and the momentum of its recoil are so small that they would be inconsistent with the uncertainty relation.

E: Okay, okay, Niels, you win. I agree that one cannot have which-way information and the interference pattern in the same experiment. You are quite right in insisting that the slit plate must also respect the laws of quantum theory. I must with pleasure compliment you on this demonstration of complementarity.

B: Hold it. Do you think that Heisenberg's relation—as above or a variant thereof—is always the mechanism that enforces complementarity?

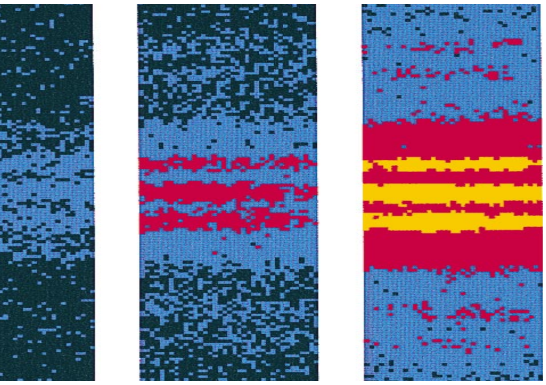
We can only speculate as to what might have been Einstein's response to the last question. For us, the answer is no. The constraints set by the uncertainty relation are not the only mechanism by which nature enforces complementarity. The negative answer is justified because we recently found that it is possible to construct which-way detectors that do not affect the motion of the observed objects significantly. That is, we envisage which-way detectors that get around the uncertainty relation.

The concept of the new which-way detector derives from a variant of the two-slit arrangement. The late Richard Feynman discussed one such variation in his admirable introduction to quantum mechanics contained in the third volume of his *Lectures on Physics.* He made the interesting observation that if one were to use electrons rather than photons, one would have another handle on interfering particles. Here he had in mind the fact that electrons themselves have wavelike aspects to their personality, just as light does. And so they would display an interference pattern in a double-slit experiment. Because electrons are charged, however, they react to electromagnetic fields, including light. As a result, we may scatter light off them to gain which-way information.

Feynman proposed a specific method to obtain such information: place a light source symmetrically between the two slits. The photons would bounce off the electrons. The direction of motion of the scattered photons would tell the experimenter whether they originate near the upper or the lower slit.

Feynman's analysis of the electron-photon collision process focuses on two variables. One is the jolt of momentum delivered to the electron. The second is the uncertainty in the precision with which the electron's position is determined. Quite similar to Einstein's recoiling-slit scenario, both quantities need to be very small if both which-way information and the interference pattern are desired, smaller indeed than permitted by Heisenberg's uncertainty relation.

The new which-way detector follows Feynman's proposal, but we devised our setup to get around the momentum jolts. Our thought experiment uses atoms rather than electrons as interfering particles. We place a small cavity—essentially a box—before each slit, so that each atom must pass through one of them before reaching the slits [*see*



**hits: one to nine photons (*blue*), 10 to 99 (*red*) and 100 or more (*yellow*). The experiment was done by Gerhard Birkl of the Max Planck Institute for Quantum Optics in Garching.**

*top illustration on next page*]. Experimenters at Munich University, the Max Planck Institute for Quantum Optics in Garching, Yale University and the École Normale Supérieure in Paris have made tremendous progress in developing the necessary experimental techniques in recent years. They can now conduct experiments in which single atoms routinely traverse cavities.

We would tune the laser beam so that each atom passing through it becomes excited. That is, the atom absorbs a short-wavelength photon from the laser and thus moves to a state of higher energy. The geometry of the cavities is such that the excited atoms are forced to release a longer-wavelength photon. (These wavelengths are comparable to that of the radiation in a microwave oven.) Locating the longer-wavelength photon would indicate the cavity, and hence the slit, through which that particular atom traversed. This setup does not fall prey to Heisenberg's uncertainty relation, given that the release of the cavity photon does not perturb the motion of the atom. To minimize extraneous signals, the cavities in real experiments would be kept ultracold. They would also have superconducting walls to guarantee a long storage time of the photons within.

Inasmuch as the detection mechanism does not affect the motion of the atoms, one might surmise that the atom would still possess its interference capability. In other words, we would have which-way information, indicating the atom's particlelike nature, and a fringe pattern, signaling its wavelike property.

This naive guess is wrong. Our analysis reveals that the which-way information and the interference pattern remain mutually exclusive. Once we obtain which-way information, the fringe pattern on the screen disappears. Instead we are left with a large splotch in the middle of the screen. We can get around Heisenberg's uncertainty relation but not around Bohr's principle of complementarity.

The way in which complementarity is upheld is rather subtle. It lies in the correlations between the atom's motional freedom and the cavity photons that effect the loss of the interference pattern. It is as if the atoms carry labels indicating through which slit they came, and atoms moving through the upper slit do not interfere with those going through the lower one. The label is the telltale photon left behind—one that has been stripped off, but a label just the same. The screen on which the interference properties could manifest themselves may be any distance away from the which-way detector cavities. That, however, does not matter. Once the correlations between a labeled atom

## Upholding Complementarity with Uncertainty

In their imaginary conversation, Niels Bohr explains to Albert Einstein why his alleged "which-way" detector could not work: it would be inconsistent with the uncertainty relation. Here we derive the quantitative reason.

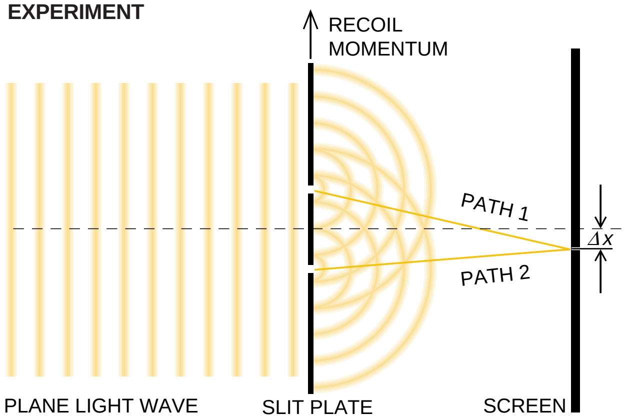
First, we denote the distance from the central bright band to the first side band by $\Delta x$. Then the position of the slit plate to the screen must be fixed rather precisely—that is, with an uncertainty, $\delta x$, markedly smaller than $\Delta x$. Otherwise the two-slit fringe pattern would not build up, and only the scatter pattern of a single slit would appear.

Einstein wanted to observe the recoil of the slit plate to glean which-way information. A photon has a momentum equal to $h\nu/c$, where $h$ is Planck's constant, $\nu$ is the frequency of the photon and $c$ the speed of light. (This photon momentum has three spatial components, but we are concerned here with the change in the component parallel to the slit plate.) The amount of recoil momentum the photon gives to the slit plate would depend on the slit through which the photon traversed (since the photon would have to be deflected by a greater amount from one slit than the other to reach the first side maximum). A bit of algebra will show that the momenta given to the two slits differ by $h/\Delta x$.

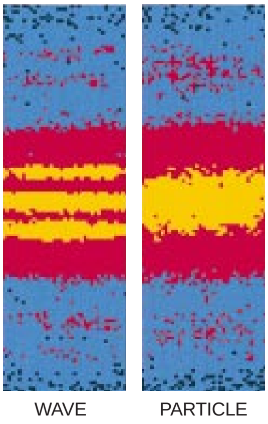
To identify the photon's path, we must know the momentum of the slit plate to a precision, $\delta p$, markedly smaller than this difference. We express the relation in mathematical form as $\delta p < h/\Delta x$. Because $\delta x$ and $\delta p$ have to be much less than $\Delta x$ and $h/\Delta x$, respectively, the product $\delta x \delta p$ must be much less than Planck's constant $h$, symbolically, $\delta x \delta p \ll h$. And so we arrive at a requirement that cannot be met in view of Heisenberg's celebrated uncertainty relation $\delta x \delta p \geq h/4\pi$, which has to be obeyed under all circumstances.

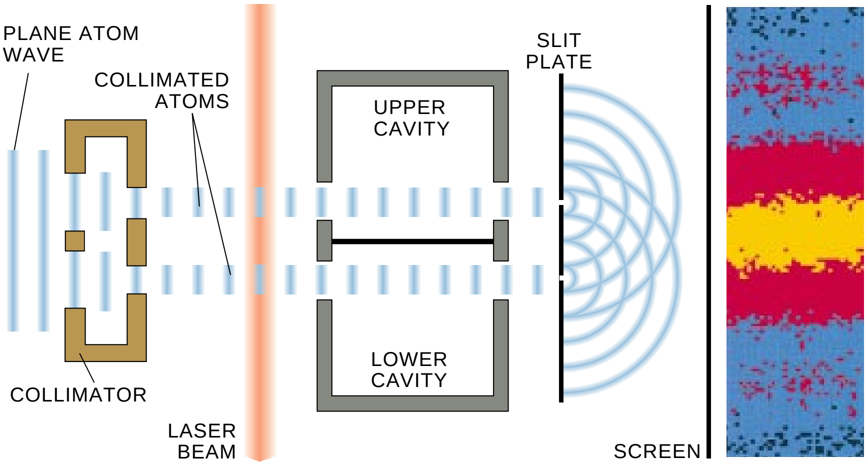
In conclusion, either $\delta x$ must be too large to allow for an interference pattern to form, or $\delta p$ must be too large to distinguish one path from the other. The argument is particularly convincing because the final requirement $\delta x \delta p \ll h$ does not depend on the details of the interference pattern, even though the quantity $\Delta x$—the spacing between the fringes—enters the reasoning at the intermediate steps.

**EINSTEIN'S GEDANKEN EXPERIMENT**



**SCREEN PATTERNS**



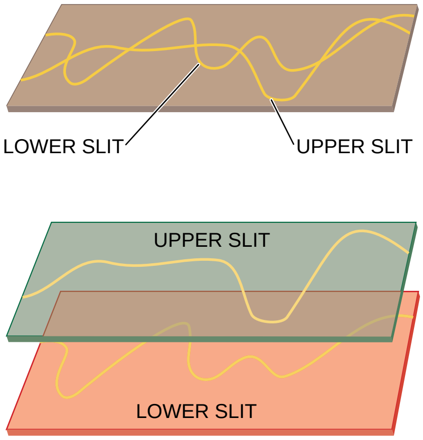


**WHICH-WAY DETECTOR uses a laser beam to excite collimated atoms (manifested as waves). The atoms drop to a lower-energy state by yielding a photon in the cavity through which they traverse. Because this emission does not affect the atom's motion, the uncertainty relation does not apply. Nevertheless, analysis indicates that the which-way information precludes interference fringes.**

and the cavity it enters become established, they remain intact.

At this point, the classical intuitionist, CI, can no longer control his temper. He turns to his friend, the quantum mechanic, QM.

CI: I have been listening patiently so far, but this is simply too much. I am willing to accept the previous arguments based on Heisenberg's uncertainty relation and agree that the presence of which-way information excludes the interference pattern. But surely that is so because in gaining the which-way information the experimenter disturbs the motion of the particle, which in turn loses its capability of interfering.



**CURVES ON A PLANE represent whether an atom passes through the upper slit or the lower one (*top*). Interference fringes correspond to the intersection points. But if correlations are established (*bottom*), the two curves are found to reside on different planes. They no longer intersect, and there is no interference.**

QM: When you say disturbs, do you think of something like an uncontrollable jolt?

CI: Yes, of course.

QM: Then you are wrong. The example of the cavity detectors demonstrates that you can have which-way information without such mechanical disturbances.

CI: I can follow your reasoning. But please help me understand the outcome. How can it be that the particle no longer interferes, although its motion has not been affected?

QM: The correlations that get established do the trick.

CI: I'm sorry, but the catchword "correlations" doesn't help me.

QM: Well, then, an analogy might be useful. Symbolize the two alternatives—the atom goes through either the upper slit or the lower slit—by two squiggly curves drawn on a horizontal plane [*see illustration at left*]. We say the curves interfere with each other whenever they cross each other. We draw the curves so they do so many times.

CI: Okay, go on.

QM: Now an additional degree of freedom is introduced—the third dimension in this analogy. The correlations are symbolized by lifting one of the curves to another plane, a few inches above the first one. Then the two curves no longer intersect—that is, they no longer interfere. And note that disregarding the correlations, achieved by ignoring the third dimension and projecting both curves onto a common plane, makes the curves appear to intersect, although they really run past each other.

CI: Aha, now I think I have a much better intuitive feeling for what is going on. In summary, the interference pattern gets lost because which-way information has become available, and this is not at all because of an uncertainty in the position of the slits or an uncontrolled jolt delivered to the atom.

QM: Yes, nothing of a random character enters.

In view of the subject's history, with its many textbook discussions invoking the uncertainty relation, many thoughtful colleagues have remained skeptical of our analysis. They have raised subtle objections to the conclusion that the motion of the atom is not perturbed. But careful calculations and a recent experiment performed in David J. Wineland's laboratory at the National Institute of Standards and Technology (NIST) in Boulder, Colo., have demonstrated convincingly that all these objections are invalid. The principle of complementarity is certainly more fundamental than is the uncertainty relation.

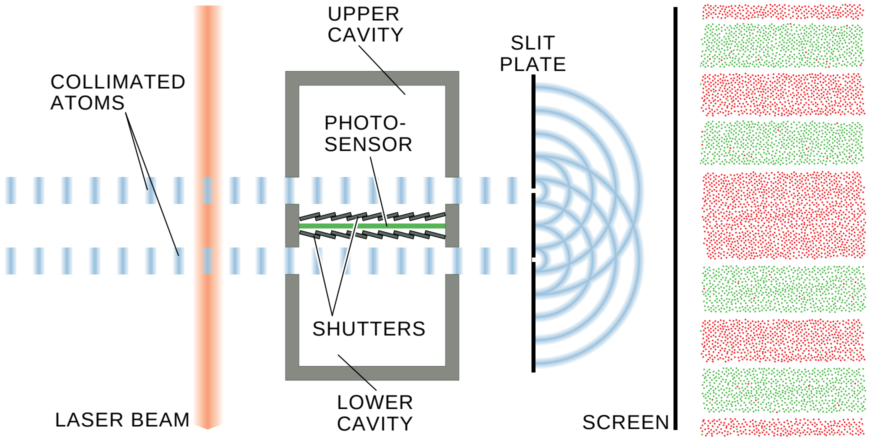
Given that which-way information precludes interference patterns, we can pose a converse question about complementarity. Suppose we erase the which-way information by absorbing the telltale photon somehow. Should not the interference pattern reemerge?

Quantum erasure would seem to make sense, although simply deleting information would not suffice in bringing back the interference pattern. It is true that an interference pattern indicates the lack of which-way information; likewise, which-way information precludes an interference pattern. But the conclusion that the lack of which-way information implies the presence of an interference pattern is a non sequitur. The answer to the question of whether the interference pattern will reemerge is therefore yes, provided that the erasure results in new correlations. Thus, the erasing has to happen under well-controlled circumstances.

The experimental realization of a quantum eraser is extremely difficult and has not yet been achieved. Instead we present a thought experiment that involves various idealizations while correctly containing all important features.

In the imagined setup, a photosensor sits between the cavities. Shutters shield the cavities from each other [*see illustration on page 92*]. As long as the shutters are closed, we have the which-way detector discussed earlier.

The experiment starts with the cavities empty and the shutters closed. We



**QUANTUM ERASER is a variation of the which-way detector. After an atom hits the screen, the shutters are opened. If the sensor absorbs the cavity photon, the spot on the screen is marked red. Otherwise, it is marked green. The red spots produce interference fringes; the green ones generate a complementary pattern.**

send an atom through the apparatus, which leaves behind a photon in one of the cavities. Of course, the chances that a particular cavity has the photon are 50–50. As the photon remains in one of the cavities, the atom reaches the screen, where it leaves a spot. Once that happens, we open the shutters simultaneously, turning the two separate cavities into a single, larger one.

Opening the shutters has an unusual effect on the photon. One might assume that the photon can now be anywhere, so that the sensor would always record a signal. But the photon is a quantum-mechanical beast. It has wave properties. Recall that before the shutters are opened, the photon has an even chance of being in either cavity. Another way to look at the situation is to say that the wave associated with the photon consists of two partial waves, one in each cavity. Now, when the shutters are opened, the photon wave is altered to fit into the new, larger cavity. The alteration can be pictured as a "melting" of the two initial, partial waves into a final, single one.

This melting can occur in different ways. If the two partial waves reinforce each other at the site of the photosensor, the instrument picks up the photon. In contrast, if the partial waves extinguish each other there, the sensor does not detect the photon. Either case is equally likely and is impossible to control or predict. Hence, the sensor has a 50 percent probability of detecting the photon left behind after the shutters are opened.

If the sensor absorbs the photon, the spot on the screen is marked red to indicate that the cavity photon has been erased. If the sensor fails to record anything, we mark the spot green. Then we start all over with the next atom. Half of the atoms will contribute to the set of red spots, half to the green ones.

What kind of pattern should emerge on the screen? Eventually all the red spots together exhibit the interference pattern that one would obtain by the two slits alone, without the which-way detector cavities. Thus, erasing the telltale photon returns the interference pattern. In contrast, the collection of green spots shows the complementary pattern: green crests at the location of red troughs, and vice versa. A black-and-white photograph of the screen would not show the interference pattern. Only by correlating the atoms to the reaction of the photosensor is the interference pattern literally brought to light.

In using QM's analogy of intersecting curves on a plane, one could state that during erasure it is recognized that the upper and lower curves consist of red and green branches. These branches are displaced to corresponding planes, so that the red branches interfere with each other. The same holds for the green ones. But because the red ones do not interfere with the green ones, one must keep them apart in order to identify the interference pattern.

Because it takes place after an atom hits the screen, erasure certainly can have no influence on the atomic motion. The choice falls to the experimenters: Do we want to know whether we registered an "upper slit" atom or a "lower slit" one, or are we interested in the complementary property of having excited the microwave-photon sensor (red) or not (green)? Both at the same time are not available: attaching labels like "upper slit" and "red" is impossible, just as the description "up and left" is unavailable when describing the magnetic properties of a silver atom. Complementarity is at work again.

The erasure scheme just described has the advantage of being readily laid out and analyzed. The experiment itself is a different matter and is still a couple of years away. The primary hurdle is the fragility of the excited atoms, which are easily destroyed.

The first erasure experiment may not use atoms as interfering objects at all. In fact, many of the most advanced interferometers do not even rely on slits. Researchers are using photon pairs as the interfering objects to study these ideas. They include investigators in the laboratories of Raymond Y. Chiao of the University of California at Berkeley, James D. Franson of Johns Hopkins University, Leonard Mandel of the University of Rochester, Yanhua Shih of the University of Maryland and Anton Zeilinger of Innsbruck University. The recent NIST experiment mentioned earlier involves a recoil-free which-way detector for light scattered by two atoms, rather than by two slits. A modification of this setup could yield a quantum erasure experiment.

Yet we do not expect the results to confound quantum mechanics. The quantum world has carefully protected itself against internal contradictions, and an unexpected finding would more likely indicate that something is wrong with the apparatus than with quantum mechanics. Despite human experimental ingenuity, nature will undoubtedly stay at least one step ahead.

## FURTHER READING

QUANTUM ERASER: A PROPOSED PHOTON CORRELATION EXPERIMENT CONCERNING OBSERVATION AND "DELAYED CHOICE" IN QUANTUM MECHANICS. M. O. Scully and K. Drühl in *Physical Review A*, Vol. 25, No. 4, pages 2208–2213; April 1982.

QUANTUM THEORY AND MEASUREMENT. John A. Wheeler and Wojciech H. Zurek. Princeton University Press, 1983.

QUANTUM OPTICAL TESTS OF COMPLEMENTARITY. M. O. Scully, B.-G. Englert and H. Walther in *Nature*, Vol. 351, No. 6322, pages 111–116; May 9, 1991.

YOUNG'S INTERFERENCE EXPERIMENT WITH LIGHT SCATTERED FROM TWO ATOMS. U. Eichmann et al. in *Physical Review Letters*, Vol. 70, No. 16, pages 2359–2362; April 19, 1993.

THE MICROMASER: A PROVING GROUND FOR QUANTUM PHYSICS. Georg Raithel, Christian Wagner, H. Walther, L. M. Narducci and M. O. Scully in *Cavity Quantum Electrodynamics*. Edited by Paul R. Berman. Academic Press, 1994.