Closed Loophole Confirms the Unreality of the Quantum World

After researchers found a loophole in a famous experiment designed to prove that quantum objects don't have intrinsic properties, three experimental groups quickly sewed the loophole shut. The episode closes the door on many "hidden variable" theories.

By Anil Ananthaswamy

Olena Shmahalo/Quanta Magazine

The theoretical physicist John Wheeler once used the phrase "great smoky dragon" to describe a particle of light going from a source to a photon counter. "The mouth of the dragon is sharp, where it bites the counter. The tail of the dragon is sharp, where the photon starts," Wheeler wrote. The photon, in other words, has definite reality at the beginning and end. But its state in the middle — the dragon's body — is nebulous. "What the dragon does or looks like in between we have no right to speak."

Wheeler was espousing the view that elementary quantum phenomena are not real until observed, a philosophical position called anti-realism. He even designed an experiment to show that if you hold on to realism — in which quantum objects such as photons always have definite, intrinsic properties, a position that encapsulates a more classical view of reality — then one is forced to concede that the future can influence the past. Given the absurdity of backward time-travel, Wheeler's experiment became an argument for anti-realism at the level of the quantum.

International Institute of Physics

Rafael Chaves, a physicist at the International Institute of Physics, and his colleagues used the emerging field of causal modeling to find a loophole in Wheeler's delayed-choice experiment.

But in May, Rafael Chaves and colleagues at the International Institute of Physics in Natal, Brazil, found a loophole. They showed that Wheeler's experiment, given certain assumptions, can be explained using a classical model that attributes to a photon an intrinsic nature. They gave the dragon a well-defined body, but one that is hidden from the mathematical formalism of standard quantum mechanics.

Chaves's team then proposed a twist to Wheeler's experiment to test the loophole. With unusual alacrity, three teams raced to do the modified experiment. Their results, reported in early June, have shown that a class of classical models that advocate realism cannot make sense of the results. Quantum mechanics may be weird, but it's still, oddly, the simplest explanation around.

Dragon Trap

Wheeler devised his experiment in 1983 to highlight one of the dominant conceptual conundrums in quantum mechanics: wave-particle duality. Quantum objects seem to act either like particles or waves, but never both at the same time. This feature of quantum mechanics seems to imply that objects have no inherent reality until observed. "Physicists have had to grapple with wave-particle duality as an essential, strange feature of quantum theory for a century," said David Kaiser, a physicist and historian of science at the Massachusetts Institute of Technology. "The idea pre-dates other quintessentially strange features of quantum theory, such as Heisenberg's uncertainty principle and Schrödinger's cat."

The phenomenon is underscored by a special case of the famous double-slit experiment called the Mach-Zehnder interferometer.

In the experiment, a single photon is fired at a half-silvered mirror, or beam splitter. The photon is either reflected or transmitted with equal probability — and thus can take one of two paths. In this case, the photon will take either path 1 or path 2, and then go on to hit either detector D1 or D2 with equal probability. The photon acts like an indivisible whole, showing us its particle-like nature.

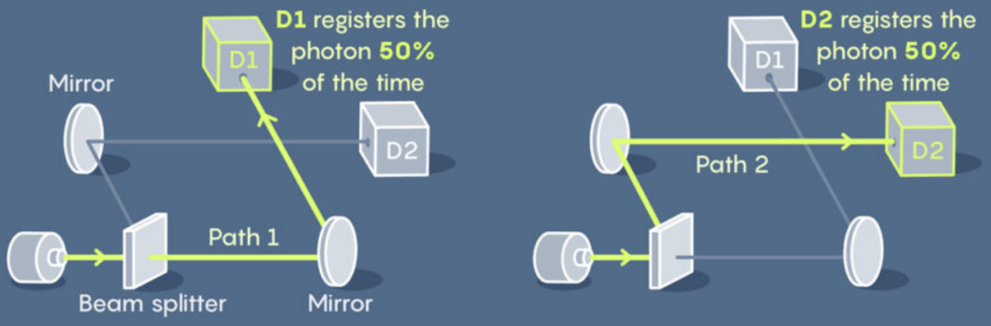
But there's a twist. At the point where path 1 and path 2 cross, one can add a second beam splitter, which changes things. In this setup, quantum mechanics says that the photon seems to take both paths at once, as a wave would. The two waves come back together at the second beam splitter. The experiment can be set up so that the waves combine constructively — peak to peak, trough to trough — only when they move toward D1. The path toward D2, by contrast, represents destructive interference. In such a setup, the photon will always be found at D1 and never at D2. Here, the photon displays its wavelike nature.

The Delayed-Choice Experiment Explained

Are quantum objects "real" when they're not observed? The delayed-choice experiment demonstrates that they can't be. It shows that an unobserved photon is neither a wave nor a particle.

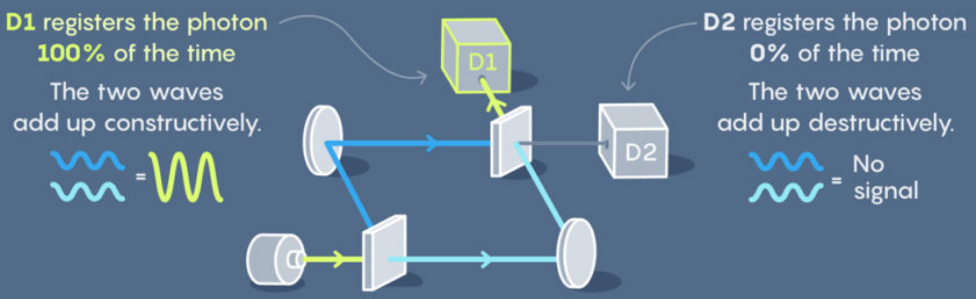
If the Photon Is a Particle

Fire a photon at a beam splitter. The photon acts as an indivisible particle. It takes either path 1 or path 2 and then goes on to hit detector D1 or D2.



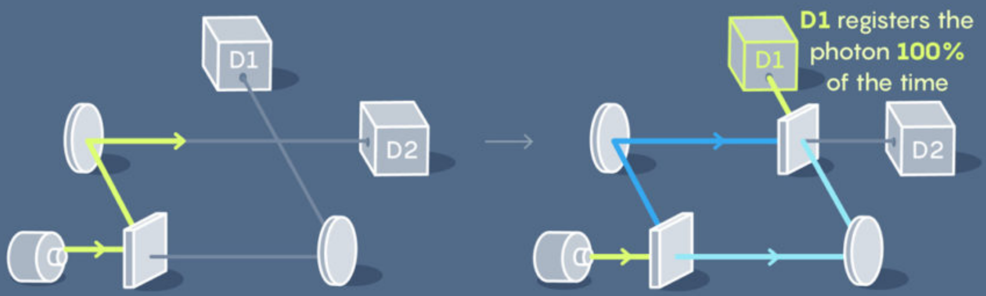
If the Photon Is a Wave

Add a second beam splitter. This time the photon acts as a wave. It seemingly splits into two waves at the first beam splitter. The waves recombine at the second. The photon always hits only one of the detectors.



Delayed Choice

Start with only one beam splitter. The photon should act like a particle. At the last moment, add the second beam splitter. The particle then suddenly changes to be wavelike, as if it was always going down both paths.



CONCLUSION: Either the addition of the beam splitter sent a signal backwards in time to influence the photon's initial behavior, or photons do not have definite, intrinsic properties when they are not being observed.

Lucy Reading-Ikkanda/Quanta Magazine

Wheeler's genius lay in asking: what if we delay the choice of whether to add the second beam splitter? Let's assume the photon enters the interferometer without the second beam splitter in place. It should act like a particle. One can, however, add the second beam splitter at the very last nanosecond. Both theory and experiment show that the photon, which until then was presumably acting like a particle and would have gone to either D1 or D2, now acts like a wave and goes only to D1. To do so, it had to seemingly be in both paths simultaneously, not one path or the other. In the classical way of thinking, it's as if the photon went back in time and changed its character from particle to wave.

One way to avoid such retro-causality is to deny the photon any intrinsic reality and argue that the photon becomes real only upon measurement. That way, there is nothing to undo.

Such anti-realism, which is often associated with the Copenhagen interpretation of quantum mechanics, took a theoretical knock with Chaves's work, at least in the context of this experiment. His team wanted to explain counterintuitive aspects of quantum mechanics using a new set of ideas called causal modeling, which has grown in popularity in the past decade, advocated by computer scientist Judea Pearl and others. Causal modeling involves establishing cause-and-effect relationships between various elements of an experiment. Often when studying correlated events — call them A and B — if one cannot conclusively say that A causes B, or that B causes A, there exists a possibility that a previously unsuspected or "hidden" third event, C, causes both. In such cases, causal modeling can help uncover C.

Chaves and his colleagues Gabriela Lemos and Jacques Pienaar focused on Wheeler's delayed choice experiment, fully expecting to fail at finding a model with a hidden process that both grants a photon intrinsic reality and also explains its behavior without having to invoke retro-causality. They thought they would prove that the delayed-choice experiment is "super counterintuitive, in the sense that there is no causal model that is able to explain it," Chaves said.

Courtesy of Gabriela Barreto Lemos

Gabriela Lemos, a physicist at the International Institute of Physics, showed how a “hidden variable” could be affecting the results of the experiment.

But they were in for a surprise. The task proved relatively easy. They began by assuming that the photon, immediately after it has crossed the first beam splitter, has an intrinsic state denoted by a “hidden variable.” A hidden variable, in this context, is something that’s absent from standard quantum mechanics but that influences the photon’s behavior in some way. The experimenter then chooses to add or remove the second beam splitter. Causal modeling, which prohibits backward time travel, ensures that the experimenter’s choice cannot influence the past intrinsic state of the photon.

Given the hidden variable, which implies realism, the team then showed that it’s possible to write down rules that use the variable’s value and the presence or absence of the second beam splitter to guide the photon to D1 or D2 in a manner that mimics the predictions of quantum mechanics. Here was a classical, causal, realistic explanation. They had found a new loophole.

This surprised some physicists, said Tim Byrnes, a theoretical quantum physicist at New York University, Shanghai. "What people didn't really appreciate is that this kind of experiment is susceptible to a classical version that perfectly mimics the experimental results," Byrnes said. "You could construct a hidden variable theory that didn't involve quantum mechanics."

"This was the step zero," Chaves said. The next step was to figure out how to modify Wheeler's experiment in such a way that it could distinguish between this classical hidden variable theory and quantum mechanics.

In their modified thought experiment, the full Mach-Zehnder interferometer is intact; the second beam splitter is always present. Instead, two "phase shifts" — one near the beginning of the experiment, one toward the end — serve the role of experimental dials that the researcher can adjust at will.

The net effect of the two phase shifts is to change the relative lengths of the paths. This changes the interference pattern, and with it, the presumed "wavelike" or "particle-like" behavior of the photon. For example, the value of the first phase shift could be such that the photon acts like a particle inside the interferometer, but the second phase shift could force it to act like a wave. The researchers require that the second phase shift is set after the first.

With this setup in place, Chaves's team came up with a way to distinguish between a classical causal model and quantum mechanics. Say the first phase shift can take one of three values, and the second one of two values. That makes six possible experimental settings in total. They calculated what they expected to see for each of these six settings. Here, the predictions of a classical hidden variable model and standard quantum mechanics differ. They then constructed a formula. The formula takes as its input probabilities calculated from the number of times that photons land on particular detectors (based on the setting of the two phase shifts). If the formula equals zero, the classical causal model can explain the statistics. But if the equation spits out a number greater than zero, then, subject to some constraints on the hidden variable, there's no classical explanation for the experiment's outcome.

Chaves teamed up with Fabio Sciarrino, a quantum physicist at the University of Rome La Sapienza, and his colleagues to test the inequality. Simultaneously, two teams in China — one led by Jian-Wei Pan, an experimental physicist at the University of Science and Technology of China (USTC) in Hefei, China, and another by Guang-Can Guo, also at USTC — carried out the experiment.

Each team implemented the scheme slightly differently. Guo's group stuck to the basics, using an actual Mach-Zehnder interferometer. "It is the one that I would say is actually the closest to Wheeler's original proposal," said Howard Wiseman, a theoretical physicist at Griffith University in Brisbane, Australia, who was not part of any team.

But all three showed that the formula is greater than zero with irrefutable statistical significance. They ruled out the classical causal models of the kind that can explain Wheeler's delayed-choice experiment. The loophole has been closed. "Our experiment has salvaged Wheeler's famous thought experiment," Pan said.

Hidden Variables That Remain

Kaiser is impressed by Chaves's "elegant" theoretical work and the experiments that ensued. "The fact that each of the recent experiments has found clear violations of the new inequality … provides compelling evidence that 'classical' models of such systems really do not capture how the world works, even as quantum-mechanical predictions match the latest results beautifully," he said.

The formula comes with certain assumptions. The biggest one is that the classical hidden variable used in the causal model can take one of two values, encoded in one bit of information. Chaves thinks this is reasonable, since the quantum system — the photon — can also only encode one bit of information. (It either goes in one arm of the interferometer or the other.) "It's very natural to say that the hidden variable model should also have dimension two," Chaves said.

Photograph by Donna Coveney

David Kaiser, a physicist and historian at MIT, wants to eliminate the possibility of any unseen experimental correlations by employing a random-number generator based on distant astrophysical objects.

But a hidden variable with additional information-carrying capacity can restore the classical causal model's ability to explain the statistics observed in the modified delayed-choice experiment.

In addition, the most popular hidden variable theory remains unaffected by these experiments. The de Broglie-Bohm theory, a deterministic and realistic alternative to standard quantum mechanics, is perfectly capable of explaining the delayed-choice experiment. In this theory, particles always have positions (which are the hidden variables), and hence have objective reality, but they are guided by a wave. So reality is both wave and particle. The wave goes through both paths, the particle through one or the other. The presence or absence of the second beam splitter affects the wave, which then guides the particle to the detectors — with exactly the same results as standard quantum mechanics.

For Wiseman, the debate over Copenhagen versus de Broglie-Bohm in the context of the delayed-choice experiment is far from settled. "So in Copenhagen, there is no strange inversion of time precisely because we have no right to say anything about the photon's past," he wrote in an email. "In de Broglie-Bohm there is a reality independent of our knowledge, but there is no problem as there is no inversion — there is a unique causal (forward in time) description of everything."

Kaiser, even as he lauds the efforts so far, wants to take things further. In current experiments, the choice of whether or not to add the second phase shift or the second beam splitter in the classic delayed-choice experiment was being made by a quantum random-number generator. But what's being tested in these experiments is quantum mechanics itself, so there's a whiff of circularity. "It would be helpful to check whether the experimental results remain consistent, even under complementary experimental designs that relied on entirely different sources of randomness," Kaiser said.

To this end, Kaiser and his colleagues have built such a source of randomness using photons coming from distant quasars, some from more than halfway across the universe. The photons were collected with a one-meter telescope at the Table Mountain Observatory in California. If a photon had a wavelength less than a certain threshold value, the random number generator spit out a 0, otherwise a 1. In principle, this bit can be used to randomly choose the experimental settings. If the results continue to support Wheeler's original argument, then "it gives us yet another reason to say that wave-particle duality is not going to be explained away by some classical physics explanation," Kaiser said. "The range of conceptual alternatives to quantum mechanics has again been shrunk, been pushed back into a corner. That's really what we are after."

For now, the dragon's body, which for a brief few weeks had come into focus, has gone back to being smoky and indistinct.