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A Quantum Delayed-Choice Experiment

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Quantum systems exhibit particle- or wavelike behavior depending on the experimental apparatus they are confronted by. This wave-particle duality is at the heart of quantum mechanics. Its paradoxical nature is best captured in the delayed-choice thought experiment, in which a photon is forced to choose a behavior before the observer decides what to measure. Here, we report on a quantum delayed-choice experiment in which both particle and wave behaviors are investigated simultaneously. The genuinely quantum nature of the photon's behavior is certified via nonlocality, which here replaces the delayed choice of the observer in the original experiment. We observed strong nonlocal correlations, which show that the photon must simultaneously behave both as a particle and as a wave.

Quantum mechanics predicts with remarkable accuracy the result of experiments involving small objects, such as atoms and photons. However, when looking more closely at these predictions we are forced to admit that they defy our intuition. Indeed, quantum mechanics tells us that a single particle can be in several places at the same time, and that distant entangled particles behave as a single physical object no matter how far apart they are (*1*).

In trying to grasp the basic principles of the theory—in particular, to understand more intuitively the behavior of quantum particles—the notion of wave-particle duality was introduced (*2*). A quantum system—for instance, a photon—may behave either as a particle or a wave. However, the way in which it behaves depends on the kind of experimental apparatus with which it is measured. Hence, both aspects, particle and wave, which appear to be incompatible, are never observed simultaneously (*3*). This is the notion of complementarity in quantum mechanics (*4*–*7*), which is central in the standard Copenhagen interpretation and has been intensely debated in the past.

In an effort to reconcile quantum predictions and common sense, it was suggested that quantum particles may in fact know in advance to which experiment they will be confronted, via a hidden variable, and could thus decide which behavior to exhibit. This simplistic argument was, however, challenged by Wheeler in his elegant "delayed choice" arrangement (*8*–*10*). In this gedanken experiment, as shown in Fig. 1A, a quantum particle is sent toward a Mach-Zender interferometer. The relative phase φ between the two arms of the interferometer can be adjusted so that the particle will emerge in output D' with certainty. That is, the interference is fully constructive in output D' and fully destructive in output D''. This measurement thus clearly highlights the wave aspect of the quantum particle. However, the observer performing the experiment has the choice of modifying the above experiment, in particular by removing the second beamsplitter of the interferometer. In this case, he will perform a which-path measurement. The photon will be detected in each mode with probability one half, thus exhibiting particle-like behavior. The main point is that the experimentalist is free to choose which experiment to perform (interference or which-path, thus testing the wave or the particle aspect) once the particle is already inside the interferometer. Thus, the particle could not have known in advance (for instance via a hidden variable) the kind of experiment with which it will be confronted because this choice was simply not made when the particle entered the interferometer. Wheeler's experiment has been implemented experimentally by using various systems, all confirming quantum predictions (*11*–*15*). In a recent experiment with single photons, a spacelike separation between the choice of measurement and the moment the photon enters the interferometer was achieved (*16*).

We explored a conceptually different take on Wheeler's experiment. Our starting point is a recent theoretical proposal (*17*) of a delayed-choice experiment based on a quantum-controlled beamsplitter, which can be in a superposition of present and absent. Hence, the interferometer can be simultaneously closed and open, thus testing both the wave and the particle behavior of the photon at the same time. Using a reconfigurable integrated quantum photonic circuit (*18*), we implemented an interferometer featuring such a quantum beamsplitter, observing continuous morphing between wave and particle behavior (*17*). However, this morphing behavior can be reproduced by a simple classical model, and this loophole also plagues both the theoretical proposal of (*17*) as well as two of its recent nuclear magnetic resonance (NMR) implementations (*19*, *20*). In order to overcome this issue, we then experimentally demonstrated a quantum delayed-choice scheme based on Bell's inequality (*21*), which allowed us to test the most general classical model. The main conceptual novelty of this scheme is that the temporal arrangement of Wheeler's original proposal—the delayed choice of closing the interferometer or not—is not necessary anymore. Instead, we certify the quantum nature of the photon's behavior by observing the violation of a Bell inequality. This demonstrates in a device-independent way—that is, without making assumptions about the functioning of the devices—that no local hidden variable model can reproduce the quantum predictions. In other words, no model in which the photon decided in advance which behavior to exhibit—knowing in advance the measurement setup—can account for the observed statistics. In our experiment, we achieve strong Bell inequality violations, hence giving an experimental refutation to such hidden variable models, up to a few additional assumptions about the implementation that are regularly used in experimental Bell tests.

Our scheme is presented in Fig. 1B. A single photon (our system) is sent through an interferometer. At the first beamsplitter, the photon evolves into a superposition of the two spatial modes, represented by two orthogonal quantum states $|0\rangle_s$ and $|1\rangle_s$. Formally, this first beam-

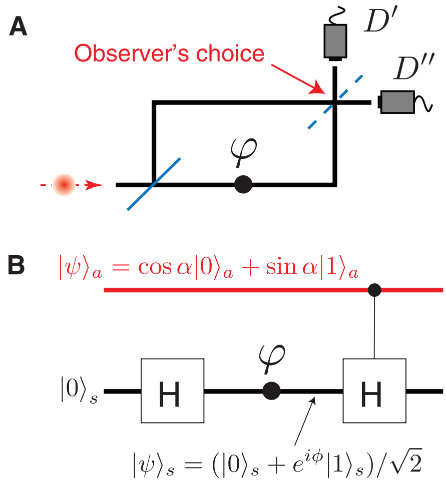

Fig. 1. Quantum delayed-choice experiment. (**A**) Schematic of Wheeler's original delayed-choice experiment. A photon is sent into a Mach-Zehnder interferometer and split into a superposition across both paths at the first beamsplitter (solid blue line). By inserting (or not) the second beamsplitter (dashed blue line), wave (or particle) behavior can be observed at detectors D' or D''. (**B**) Schematic of the quantum delayed-choice experiment. The second beamsplitter is now a quantum beamsplitter (represented by a controlled-Hadamard operation), which can be set in a superposition of present and absent by controlling the state of an ancilla photon $|\psi\rangle_a$.

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splitter is represented by a Hadamard operation (22), which transforms the initial photon state $|0\rangle_s$ into the superposition $(|0\rangle_s + |1\rangle_s)/\sqrt{2}$. A phase shifter then modifies the relative phase between the two modes, resulting in the state $|\psi\rangle_s = (|0\rangle_s + e^{i\varphi}|1\rangle_s)/\sqrt{2}$. Both modes are then recombined on a second beamsplitter before a final measurement in the logical $(\{|0\rangle_s, |1\rangle_s\})$ basis. In the standard delayed-choice experiment, the presence of this second beamsplitter is controlled by the observer (see Fig. 1A). For a closed interferometer, the statistics of the measurements at detectors D' and D'' will depend on the phase φ, revealing the wave nature of the photon. For an open interferometer, both detectors will click with equal probability, revealing the particle nature of the photon.

Here, on the contrary, the presence of the second beamsplitter depends on the state of an ancillary photon. If the ancilla photon is prepared in the state $|0\rangle_a$, no beamsplitter is present; hence, the interferometer is left open. Formally, this corresponds to the identity operator acting on $|\psi\rangle_s$, resulting in the state

$$|\psi\rangle_{s,\text{particle}} = \frac{1}{\sqrt{2}}(|0\rangle_s + e^{i\varphi}|1\rangle_s) \qquad (1)$$

The final measurement (in the $\{|0\rangle_s, |1\rangle_s\}$ basis) indicates which path the photon took, revealing the particle nature of the photon. The measured intensities in both output modes are equal and phase-independent, $I_{D'} = I_{D''} = 1/2$.

If, however, the ancilla photon is prepared in the state $|1\rangle_a$, the beamsplitter is present, and the interferometer is therefore closed. Formally, this corresponds to applying the Hadamard operation to $|\psi\rangle_s$, resulting in the state

$$|\psi\rangle_{s,\text{wave}} = \cos\frac{\varphi}{2}|0\rangle_s - i\,\sin\frac{\varphi}{2}|1\rangle_s \qquad (2)$$

The final measurement gives information about the phase φ that was applied in the interferometer, but indeed not about which path the photon took. The measured intensities are $I_{D'} = \cos^2(\varphi/2)$ and $I_{D''} = \sin^2(\varphi/2)$.

The main feature of this quantum controlled beamsplitter is that it can be put in a superposition of being present and absent. Indeed, if the ancilla photon is initially in a superposition—for instance, in the state $|\psi\rangle_a = \cos\alpha|0\rangle_a + \sin\alpha|1\rangle_a$—then the global state of the system evolves into

$$|\Psi_f(\alpha,\varphi)\rangle = \cos\alpha|\psi\rangle_{s,\text{particle}}|0\rangle_a + \sin\alpha|\,\psi\rangle_{s,\text{wave}}|1\rangle_a \qquad (3)$$

The system and ancilla photons now become entangled, when $0 < \alpha < \pi/2$.

The measured intensity at detector D' is then given by

$$I_{D'}(\varphi,\alpha) = I_{\text{particle}}(\varphi)\cos^2\alpha + I_{\text{wave}}(\varphi)\sin^2\alpha = \frac{1}{2}\cos^2\alpha + \cos^2\left(\frac{\varphi}{2}\right)\sin^2\,\alpha \qquad (4)$$

whereas intensity at D'' is $I_{D''}(\varphi, \alpha) = 1 - I_{D'}(\varphi, \alpha)$.

We fabricated the quantum circuit shown in Fig. 2 in a silica-on-silicon photonic chip (*18*). The Hadamard operation is implemented by a directional coupler of reflectivity 1/2, which is equivalent to a 50/50 beamsplitter. The controlled-Hadamard (CH) is based on a nondeterministic control-phase gate (*23*, *24*). The system and ancilla photon pairs are generated at 808 nm via parametric down conversion and detected with silicon avalanche photodiodes at the circuit's output.

We first characterized the behavior of our setup for various quantum states of the ancilla photon. We measured the output intensities $I_{D'}(\varphi, \alpha)$ and $I_{D''}(\varphi, \alpha)$ for $\alpha \in [0, \pi/2]$, and $\varphi \in [-\pi/2, 3\,\pi/2]$. In particular, by increasing the value of α we observe the morphing between a particle measurement ($\alpha = 0$) and a wave measurement ($\alpha = \pi/2$). For $\alpha = 0$ (no beamsplitter), the measured intensities are independent of φ. For $\alpha = \pi/2$, the beamsplitter is present, and the data shows interference fringes. Our results are in excellent agreement with theoretical predictions (Fig. 3).

To achieve our main goal—to refute models in which the photon knows in advance with which setup it will be confronted—we must go one step further. Indeed, the result of Fig. 3 does not refute such models. Although we have inserted the ancilla photon in a superposition, hence testing both wave and particle aspects at the same time, we have in fact not checked the quantum nature of this superposition. This is because the final measurement of the ancilla photon was made in the logical $(\{|0\rangle_a, |1\rangle_a\})$ basis. Therefore, we cannot exclude the fact that the ancilla may have been in a statistical mixture of the form $\cos^2\alpha|0\rangle\langle 0|_a + \sin^2\alpha|1\rangle\langle 1|_a$, which would lead to the same measured statistics. Hence, the data can be explained by a classical model, in which the state of the ancilla represents a classical variable (a classical bit) indicating which measurement, particle or wave, will be performed. Because the state of the ancilla may have been known to the system photon in advance—indeed, here no delayed choice is performed by the observer—no conclusion can be drawn from this experiment. This loophole also plagues the recent theoretical proposal of (*17*), as well as two of its NMR implementations (*19*, *20*).

In order to show that the measurement choice could not have been known in advance, we must ensure that our quantum controlled beamsplitter behaves in a genuine quantum way. In particular, we must ensure that it creates entanglement between the system and ancilla photons, which is the clear signature of a quantum process. The global state of the system and ancilla photons, given in Eq. 3, is entangled for all values $0 < \alpha < \pi/2$. Because $\langle\psi_{\text{particle}}|\psi_{\text{wave}}\rangle \sim \cos\varphi$, the degree of entanglement depends on φ and α; in particular, for $\alpha = \pi/4$ and $\varphi = \pi/2$ the state in Eq. 3 is maximally entangled.

In order to certify the presence of this entanglement, we tested the Clauser-Horne-Shimony-Holt (CHSH) Bell inequality (*25*), the violation

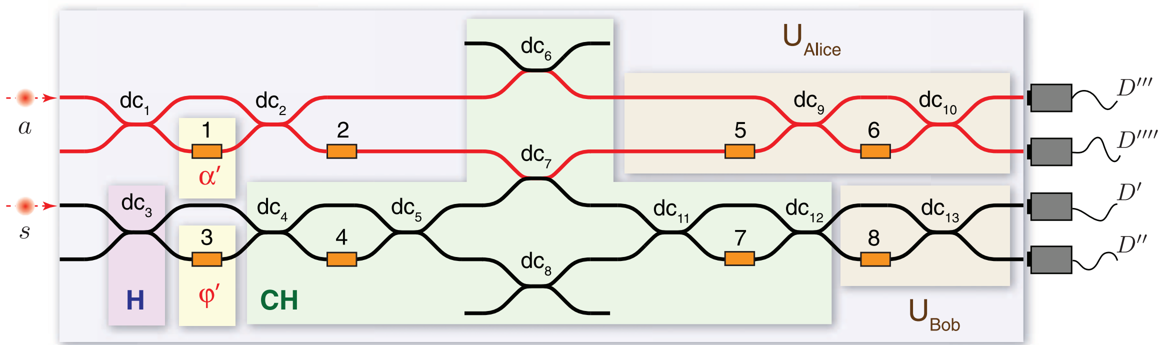

Fig. 2. Implementation of the quantum delayed-choice experiment on a reconfigurable integrated photonic device. Nonentangled photon pairs are generated by using type I parametric down-conversion and injected into the chip by using polarization maintaining fibers (not shown). The system photon (*s*), in the lower part of the circuit, enters the interferometer at the Hadamard gate (*H*). A relative phase φ is applied between the two modes of the interferometer. Then, the controlled-Hadamard (CH) is implemented by a nondeterministic CZ gate with two additional MZ interferometers. The ancilla photon (*a*), in the top part of the circuit, is controlled by the phase shifter α, which determines the quantum state of the second beamsplitter—a superposition of present and absent. Last, the local measurements for the Bell test are performed through single-qubit rotations (U_A and U_B) followed by APDs. The circuit is composed of directional couplers of reflectivity 1/2 (dc_{1-5} and dc_{9-13}) and 1/3 (dc_{6-8}) and resistive heaters (orange rectangles) that implement the phase shifters (*25*).

of which would imply in a device-independent way that the measured data could not have been produced by a classical model. In the CHSH Bell scenario, each party (here, Alice holds the system photon while Bob holds the ancilla photon) chooses among two possible measurement settings, denoted $x = 0,1$ for Alice and $y = 0,1$ for Bob. Each measurement is dichotomic, giving a binary result $A_x = \pm 1$ and $B_y = \pm 1$. The CHSH inequality then reads

$$S = \langle A_0 B_0 \rangle + \langle A_0 B_1 \rangle + \langle A_1 B_0 \rangle - \langle A_1 B_1 \rangle \leq 2 \quad (5)$$

This represents a Bell inequality in the sense that any local model must satisfy it.

Indeed, this inequality can be violated by making judiciously chosen local measurements on certain entangled states. We measured S for the output state $|\Psi_f(\alpha, \varphi)\rangle$ for $\alpha \in [0, \pi/2]$ and $\varphi \in [-\pi/2, 3\pi/2]$. We tailored the local measurement operators of Alice and Bob [adjusting phase shifters 5, 6, and 8 (*26*)] for the maximally entangled state $|\Psi_f(\alpha = \pi/4, \varphi = \pi/2)\rangle$. Hence, for this state we expect the maximal possible violation of the CHSH inequality in quantum mechanics—namely, $S = 2\sqrt{2}$ (*27*). The choice of apparatus in Wheeler's original setup is here, in some sense, replaced by the choice of measurement settings for the Bell test. The latter choice is nevertheless conceptually different from the former, in that it can be performed after the photon left the interferometer.

Experimentally, we observed a maximal violation of $S = 2.45 \pm 0.03$ for $\alpha = \pi/4$ and $\varphi = \pi/2$, which is in good agreement with theoretical predictions (Fig. 4). Therefore, our data could not have been accounted for by any model in which the system photon would have known in advance whether to behave as a particle or as a wave. However, for this claim to hold without making further assumptions, a loophole-free Bell inequality violation is required. This is not the case in our experiment, as in all optical Bell tests performed so far, which forces us to make a few additional assumptions. We make the standard fair-sampling assumption (allowing us to discard inconclusive results and postselect only coincidence events), which must here be slightly strengthened because of the nondeterministic implementation of the controlled Hadamard operation. We must also assume independence between the photon source and the choice of measurement setting used in the Bell inequality test. As usual, if the photons could know in advance the choice of measurement setting in the Bell test, then a local model can mimic Bell inequality violations. It would be interesting to perform a more refined experiment in which these assumptions could be relaxed (*28*, *29*).

We have reported on a quantum delayed-choice experiment, giving a novel demonstration of wave-particle duality, Feynman's "one real mystery" in quantum mechanics. In our experiment, the delayed choice of Wheeler's proposal is replaced by a quantum controlled beamsplitter followed by a Bell inequality test. In this way, we demonstrate genuine quantum behavior of single photons. The demonstration of a quantum controlled beamsplitter shows that a single measurement device can continuously tune between particle and wave measurements, hence pointing toward a more refined notion of complementarity in quantum mechanics (*17*, *30*–*32*).

Note added in proof. We note a related work of Kaiser *et al.* (*33*), who performed a similar quantum delayed-choice experiment.

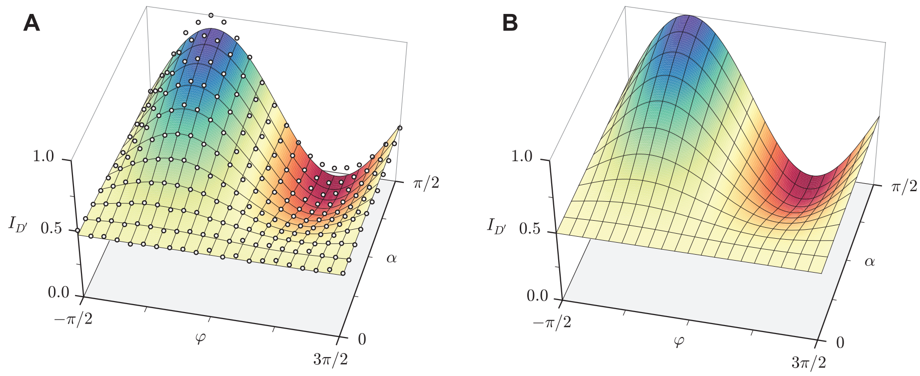

Fig. 3. Characterization of the continuous transition between wave and particle behavior. (**A**) Measured and (**B**) simulated intensity at detector D' when continuously tuning the state of the ancilla photon $|\psi\rangle_a$. The experimental data (white dots) were fitted by using Eq. 4. The data shows excellent agreement with theoretical predictions. Error bars due to Poissonian noise are smaller than the data points; hence, they are not drawn. The discrepancy between the experimental and theoretical results is not due to statistical fluctuations but to imperfection in the device calibration.

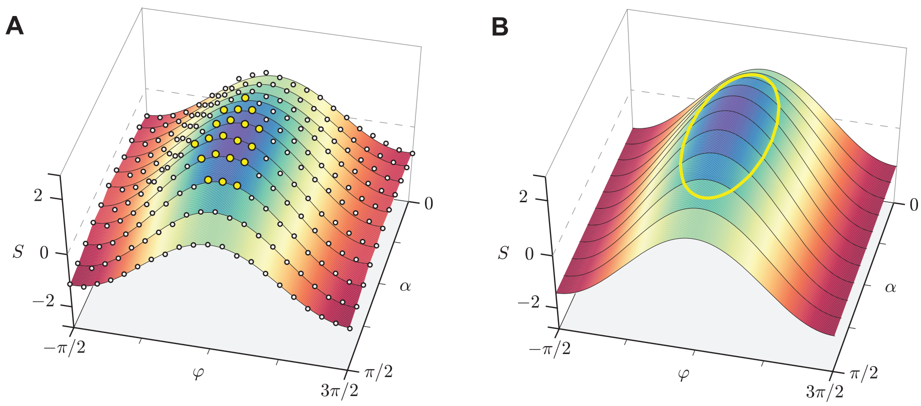

Fig. 4. Experimental Bell-CHSH inequality test. (**A**) Measured and (**B**) simulated Bell-CHSH parameter S (Eq. 1). When the CHSH inequality is violated—when $S > 2$ [yellow dots in (A) and yellow circle in (B)]—no local hidden variable model can explain the observed data, hence demonstrating genuine quantum behavior. The maximal experimental violation ($S = 2.45 \pm 0.03$) is achieved for $\alpha = \pi/4$ and $\varphi = \pi/2$, as expected. The data are in excellent agreement with theoretical predictions. Error bars due to Poissonian noise are smaller than the data points; hence, they are not drawn. The discrepancy between the experimental and theoretical results is not due to statistical fluctuations but to imperfection in the device calibration.

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Fig. S1

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Entanglement-Enabled Delayed-Choice Experiment

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Wave-particle complementarity is one of the most intriguing features of quantum physics. To emphasize this measurement apparatus–dependent nature, experiments have been performed in which the output beam splitter of a Mach-Zehnder interferometer is inserted or removed after a photon has already entered the device. A recent extension suggested using a quantum beam splitter at the interferometer's output; we achieve this using pairs of polarization-entangled photons. One photon is tested in the interferometer and is detected, whereas the other allows us to determine whether wave, particle, or intermediate behaviors have been observed. Furthermore, this experiment allows us to continuously morph the tested photon's behavior from wavelike to particle-like, which illustrates the inadequacy of a naive wave or particle description of light.

Although the predictions of quantum mechanics have been verified with marked precision, subtle questions arise when attempting to describe quantum phenomena in classical terms (*1*, *2*). For example, a single quantum object can behave as a wave or as a particle. This concept is illustrated by Bohr's complementarity principle (*3*) which states that, depending on the measurement apparatus, either wave or particle behavior is observed (*4*, *5*). This is demonstrated by sending single photons into a Mach-Zehnder interferometer (MZI) followed by two detectors (Fig. 1A) (*6*). If the MZI is closed [that is, if the paths of the interferometer are recombined at the output beam splitter (BS_2)], the probabilities for a photon to exit at detectors D_a and D_b depend on the phase difference θ between the two arms. The which-path information remains unknown, and wavelike intensity interference patterns are observed (Fig. 1B). On the other hand, if the MZI is open (i.e., if BS_2 is removed), each photon's path can be known, and consequently, no interference occurs. Particle behavior is said to be observed, and the detection probabilities at D_a and D_b are equal to ½, independent of the value of θ (Fig. 1C). In other words, these two different configurations—BS_2 present or absent—give different experimental results. Recently, Jacques *et al.* have shown that, even when performing Wheeler's original gedanken experiment (*7*) in which the configuration for BS_2 is chosen only after the photon has passed the entrance beam splitter BS_1, Bohr's complementarity principle is still obeyed (*8*). Intermediate cases, in which BS_2 is only partially present, have been considered in theory and led to a more general description of Bohr's complementarity principle expressed by an inequality limiting the simultaneously available amount of interference (signature of wavelike behavior) and which-path information (particle-like behavior) (*9*, *10*). This inequality has also been confirmed experimentally in delayed-choice configurations (*11*, *12*).

We take Wheeler's experiment one step further by replacing the output beam splitter by a quantum beam splitter (QBS), as theoretically proposed of late (*13*, *14*). In our experiment (Fig. 2), we exploit polarization entanglement as a resource for two reasons. First, doing so permits implementing the QBS. Second, it allows us to use one of the entangled photons as a test photon sent to the interferometer and the other one as a corroborative photon. Here, as opposed to previous experiments (*8*, *11*), the state of the interferometer remains unknown, as does the wave or particle behavior of the test photon, until we detect the corroborative photon. By continuously modifying the type of measurement performed on the corroborative photon, we can morph the test photon from wave to particle behavior, even after the test photon was detected. To exclude interpretations based on either mixed states, associated with preexisting state information (*15*), or potential communication between the two photons, the presence of entanglement is verified via the violation of the Bell inequalities with a space-like separation (*16*–*18*).

The QBS is based on the idea that when a photon in an arbitrary polarization state enters an interferometer that is open for $|H\rangle$ (horizontally polarized) and closed for $|V\rangle$ (vertically polarized) photons, the states of the interferometer and the photon become correlated. Our apparatus, shown in the right-hand side of Fig. 2 and detailed in fig. S1, therefore reveals a particle behavior for the $|H\rangle$ component of the photon state and a wave behavior for the $|V\rangle$ component. Note that such an experiment has been realized with the use of single photons prepared in a coherent superposition of $|H\rangle$ and $|V\rangle$ (*12*). However, we take this idea a step further by achieving genuine quantum behavior for the output beam splitter by exploiting an intrinsically quantum resource, entanglement. This allows us to entangle the quantum beam splitter and test photon system with the corroborative photon. Thus, measurement of the corroborative photon enables us to project the test photon–QBS system into an arbitrary coherent wave-particle superposition, which is a purely quantum object. In other words, our QBS is measured by another quantum object, which projects it into a particular superposition of present and absent states. More precisely, we use as a test photon one of the photons from the maximally polarization-entangled Bell state $|\Phi^+\rangle = \frac{1}{\sqrt{2}}(c_H^\dagger t_H^\dagger + c_V^\dagger t_V^\dagger)|vac\rangle$, produced at the wavelength of 1560 nm using the source described in (*19*). Here, using the notation of Fig. 2,

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