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Realization of quantum Wheeler's delayed-choice experiment

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I. MACH-ZEHNDER INTERFEROMETER

It is worth noting that, although modern experiments[1–3] are described in the language of a traditional double-slit experiment here, a Mach-Zehnder interferometer (MZI) is the device that is actually used. An MZI is equivalent to a double-slit device, and easier to use experimentally. The first beam splitter (BS) in the MZI corresponds to the double slits, while the second BS plays the same role as the screen. When this second BS is present, the detectors observe the interference fringes; when the BS is removed, the detectors see an invariant light intensity, and each detector corresponds to one path of the photons.

II. EXPLANATION FOR QUANTUM DELAY-CHOICE EXPERIMENT

In both Fig. 1a and Fig. 1b (see main text), $|0\rangle$ represents the initial path state of the photon. The first Hadamard (H) gate stands for the splitting of the photon path, i.e., the first BS in the MZI. After that, a φ phase is added. The second H gate (corresponding to the second BS in the MZI, i.e., the detecting device) is controlled by an ancilla $|pol\rangle = sin\alpha|V\rangle + cos\alpha|H\rangle$. The main difference between these two schemes is the control method of this second H gate. In the classical case (an example of which is in the reference[3], the ancilla is first detected on the eigenbasis $\{|H\rangle, |V\rangle\}$ to generate a series of random numbers p. This process destroys the possibility of the detecting device occupying a quantum-superposition state. The result p is then used to control which classical eigenstate of the H gate (i.e., the presence or absence of the second BS in the MZI) should be selected. This control method is the "classical" control of the detecting device. In this case, the choice of state of the second H gate (the detecting device) is made after the photon has passed the first H gate but before it arrives at the second H gate. In the quantum case, the ancilla is directly used to control the second H gate, which preserves the quantum superposition of the ancilla for the controlled H gate. In this case, the H gate can occupy a quantum state (superposition of the presence and absence of the second BS in the MZI), providing a "quantum" control method. In this case, the choice of which type of detecting device the photon goes through can even be made after the photon has passed the detecting device (the controlled H gate) until the ancilla state is detected. With this quantum control, we can see morphing between the wave property and the particle property of light. Strikingly, we can also see the quantum superposition of these two properties by collapsing the ancilla on a quantum-superposition state.

III. ANALYSES FOR FIGURE 4

To do the theoretical simulations in Fig. 4 (main text), we first derived the theoretical expressions of the probability that the photons take Path 1 from equation (2) and equation (3) in Methods, using a computer to find the maximum and minimum points. From these values, the theoretical values of the center, visibility and ratio were calculated. In Fig. 4a, we can see an oscillation of the center as α varies for the quantum case, but no oscillation appears in the classical case. In Fig. 4b, the visibility of the quantum case is either higher or lower than that of the classical case, and the curve is asymmetrical. For example, when $\alpha = \frac{\pi}{4}$, the visibility of the classical case goes down to 0.452, but the visibility of the quantum case remains as high as 0.835. In Fig. 4c, the ratio, which is connected to the symmetry of the probability curves in Fig. 3, is also modulated. For the classical case, all of the probability curves (see Fig. 3 in main text) are symmetrical, and the ratio remains 0.5. For the quantum case, however, the ratio can be either lower or higher than 0.5, which means that the probability curves can be highly asymmetrical.

IV. MORE DISCUSSIONS

We have seen the different behaviors of the quantum wave-particle superposition and the classical wave-particle mixture, but we must still determine the cause of these differing results. The difference is provided by the quantum interference between the photon's wave and particle properties. According to equation (3) in Methods, the non-normalized probabilities to find a photon in Path 0 or 1 are

$$\begin{aligned} \tilde{P}_{0q} &= P_{0c} + I_0(\varphi, \alpha, \delta_0), \\ \tilde{P}_{1q} &= P_{1c} + I_1(\varphi, \alpha, \delta_1), \end{aligned} \tag{1}$$

where $P_{0c} = \frac{1}{2} + \frac{1}{2}cos^2\alpha cos\varphi$ and $P_{1c} = \frac{1}{2} - \frac{1}{2}cos^2\alpha cos\varphi$ are the corresponding probabilities in the classical-mixture case. Here, we derive additional terms in both $\tilde{P}_{0q}$ and $\tilde{P}_{1q}$: $I_0(\varphi, \alpha, \delta_0) = \sqrt{2}sin\alpha cos\alpha cos\frac{\varphi}{2}cos(\frac{\varphi}{2} + \delta_0)$ and $I_1(\varphi, \alpha, \delta_1) = -\sqrt{2}sin\alpha cos\alpha sin\frac{\varphi}{2}sin(\frac{\varphi}{2} - \delta_1)$.

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These terms bridge the wave state and the particle state, introducing the quantum interference between these two states. They do not only depend on α, but also depend on the phase φ. They also introduce additional oscillations with different centers, amplitudes and phases. They even introduce oscillation of the total non-normalized probability. Therefore, after normalization, the quantum-case probability curves in Fig. 3 (main text) no longer coincide with the classical-case curves.

Actually, the introduction of a secondary bit to control the detecting device had been considered in the previous work called delayed-choice quantum eraser[4]. However, in that experiment, the secondary bit corresponded to the information of which path (Path0 or Path1) the photon took, but not the wave-particle properties (whether a single path or both paths were taken, do not care about which path). This difference causes the quantum-eraser experiment to be classified as a classical delayed-choice experiment.

V. QUANTUM DOT SAMPLE AND SOME NOTES ON THE EXPERIMENTAL SETUP

Our InAs/GaAs self-assembled quantum dot sample is grown by the molecular beam epitaxy method. A single dot is isolated by a 2 um pinhole on the 100 nm gold film covering the sample's surface, and a single peak on the spectrum is separated by a 1200 $groove/mm$ grating and a slit. The single photons are detected by the APDs and counted by a PCI counter card. The total count is approximately 12000 $/s$, and the background and dark count is approximately 150 $/s$. The time analyzer consists of a time-amplitude converter (TAC) and a multiple channel analyzer (MCA).

We have three notes on the experimental setup: 1) Instead of the standard BS, we used beam displacers (BDs) to construct the MZI. The BD moves the extraordinary beam to a parallel path separated from the ordinary beam by 4 mm, which makes the MZI stable in our experiment. 2) A large number of half-wave plates (HWP) are used in this setup to change the polarizations of the light to match the optical axis of the BD. We have not shown these HWPs in the Fig. 2 (main text); instead, we label the photon polarizations with arrows on the beam path. 3) The arrows are the real directions of photon polarization, while $|H\rangle$ and $|V\rangle$ are only the notations. They are not exactly the same because of the complexity of the setup, but coincide at the final output ports (before the detectors).

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