A twofold quantum delayed-choice experiment in a superconducting circuit

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Wave-particle complementarity lies at the heart of quantum mechanics. To illustrate this mysterious feature, Wheeler proposed the delayed-choice experiment, where a quantum system manifests the wave- or particle-like attribute, depending on the experimental arrangement, which is made after the system has entered the interferometer. In recent quantum delayed-choice experiments, these two complementary behaviors were simultaneously observed with a quantum interferometer in a superposition of being closed and open. We suggest and implement a conceptually different quantum delayed-choice experiment by introducing a which-path detector (WPD) that can simultaneously record and neglect the system’s path information, but where the interferometer itself is classical. Our experiment is realized with a superconducting circuit, where a cavity acts as the WPD for an interfering qubit. Using this setup, we implement the first twofold delayed-choice experiment, which demonstrates that the system’s behavior depends not only on the measuring device’s configuration that can be chosen even after the system has been detected but also on whether we a posteriori erase or mark the which-path information, the latter of which cannot be revealed by previous quantum delayed-choice experiments. Our results represent the first demonstration of both counterintuitive features with the same experimental setup, significantly extending the concept of quantum delayed-choice experiment.

INTRODUCTION

Wave-particle duality is among the most fundamental properties of quantum mechanics. According to Bohr’s principle of complementarity, a quantum system has complementary and mutually exclusive properties that cannot be observed at the same time (1–3). Whether a quantum system behaves as a wave or as a particle depends on the arrangement of measurement apparatus, as demonstrated by the delayed-choice experiment with a Mach-Zehnder (MZ) interferometer, in which the choice of inserting the second beam splitter BS2 or not is made after the photon has entered the interferometer (4–9), as shown in Fig. 1A. When BS2 is inserted, no path information is available so that the probability for detecting the photon at either outport depends on the relative phase φ between the two paths, showing the interference effect. In the absence of BS2, detecting the photon at each outport unambiguously reveals which route the photon has traveled so that no interference appears. The delayed-choice nature rules out the assumption that the photon could know beforehand what type of experimental apparatus it will be confronted with, and then behaves accordingly.

Recently, a quantum delayed-choice experiment was proposed by Inicioiu and Terno (10), where the action of BS2 is controlled by a quantum ancilla: When the ancilla is in the state |0⟩, BS2 is removed; for the ancilla state |1⟩, BS2 is inserted. The process, in terms of quantum circuits (11), is shown in Fig. 1B, where the Hadamard gates H1 and H2 represent the corresponding beam splitters. When the ancilla is in a superposition of |0⟩ and |1⟩, the wave- and particle-like behaviors of the test system can be observed at the same time; these two complementary phenomena are encoded in the same output state and postselected depending on the measured value of the ancilla. This proposal has been successfully demonstrated in experiments using photons (12–14) and other systems (15–17).

Here, we propose and experimentally demonstrate a twofold quantum delayed-choice experiment by introducing a which-path detector (WPD) in a superposition of its on and off states. Unlike the beam splitter that is used to split or recombine the particle’s path, the WPD is used to determine the path taken by the particle. Compared to the qubit used to control the action of the output beam splitter in the previous quantum delayed-choice experiments (10, 12–17), a quantum WPD works in a larger Hilbert space and thus enables one to have two chances to postselect the behavior of the test quantum system, as will be shown. As illustrated in Fig. 1C through a double-slit apparatus, when the WPD is in its on state |O⟩, it collects the path information of the incoming quantum particle and changes its state to |O1⟩ and |O2⟩, which correspond to paths 1 and 2 of the particle with wave functions ψ1(r) and ψ2(r), respectively. When the WPD is in its off state |F⟩, it does not record any information of the incoming particle. If the WPD starts at a superposition of its on and off states (|O⟩ + |F⟩)/√2, the combined state of the WPD and the quantum particle becomes

$$|Φ(r)⟩ = \frac{1}{2} \left[ (|ψ_1(r)⟩|O_1⟩ + |ψ_2(r)⟩|O_2⟩) + \left( |ψ_1(r)⟩ + |ψ_2(r)⟩ \right) |F⟩ \right]$$

(1)

If we measure the interference pattern of the quantum particle in the state |Φ(r)⟩, the interference fringes given by the cross terms 〈ψ1(r)|ψ2(r)⟩ appear or disappear, depending on whether we postproject the WPD’s state to the vector |F⟩ or the subspace O spanned by |O1⟩ and |O2⟩. This corresponds to a quantum delayed-choice experiment enabled by a quantum WPD in a classical interferometer instead of by a quantum interferometer, which is conceptually different.
from previous quantum delayed-choice experiments (10, 12–17). This important difference leads to a distinction of the outcome: In our experiment, we can later erase the which-path information of the quantum particle (18–23) to recover the interference fringes even after we have projected the WPD to the “on” subspace O. This is achieved by measuring the WPD in the subspace O along the basis of $$|\pm\rangle = (|O_1\rangle \pm |O_2\rangle) / \sqrt{2}$$, which fully restores the interference terms. In contrast, if we measure the WPD in the basis of $$|\{O_1\}, |\{O_2\}\rangle$$, the interference fringe is completely lost. Therefore, we can realize a twofold quantum delayed-choice experiment, where we have two chances to choose the wave or particle behavior of the already detected quantum system, pushing the test of wave-particle complementarity to an unprecedented level of controllability.

Previous experiments either demonstrated that the behavior of a system depends on the detecting device’s configuration that can be arranged in a delayed-choice manner (4–10, 12–17) or showed that one can a posteriori choose if the system behaves as a wave or as a particle by erasing or marking the which-path information stored in the WPD (18–23). We further note that the latter feature cannot be demonstrated by the previous quantum delayed-choice experiments, where the which-path information associated with the system’s particle behavior was acquired by classical detectors after the interferometer, instead of being stored in the state of another quantum system, and thus cannot be erased at a later time (10, 12–17). Our experiment, realized with a superconducting circuit, demonstrates both features with the same measurement apparatus for the first time, greatly extending the concept of quantum delayed-choice experiment. We note that the quantum delayed-choice experiment reported by Zheng et al. (17) was also performed with a superconducting circuit, where the microwave field in a resonator prepared in a cat state served as a beam splitter for the quantum state of a qubit, and the interferometer is in a superposition of being closed and open. In distinct contrast, in the present experiment, the field in a cavity plays the role of a WPD for a qubit, and the interferometer is definitely closed; the delayed choice is enabled by the quantum superposition of the WPD. Furthermore, here, the which-path information associated with the postselected qubit’s particle-like behavior is stored in the cavity, instead of being detected after the second beam splitter–like transformation so that one has the second chance to a posteriori choose if the qubit behaves as a wave or as a particle by erasing or marking the which-path information.

**RESULTS**

**Observing transition between wave- and particle-like behaviors**

We implement the twofold quantum delayed-choice experiment with a superconducting Ramsey interferometer. The circuit diagram is shown in Fig. 1D, which is similar to that of an MZ interferometer, with the $$\pi/2$$ pulses $$P_1$$ and $$P_2$$ representing the beam splitters for the quantum state of a qubit, whose basis vectors $$|g\rangle$$ and $$|e\rangle$$ correspond to the two paths in the MZ interferometer. Here, each of the classical microwave pulses produces a $$\pi/2$$ rotation on the Bloch sphere. The qubit, initially in the state $$|g\rangle$$, is transformed to the superposition state $$(|g\rangle + |e\rangle) / \sqrt{2}$$ by $$P_1$$. Then, a relative phase shift between $$|g\rangle$$ and $$|e\rangle$$ is introduced to get the state $$(|g\rangle + e^{i\phi}|e\rangle) / \sqrt{2}$$, mimicking the relative phase $$\phi$$ between the two interferometer arms. The WPD is represented by a cavity in the dispersive region, with its coupling to the qubit described by the Hamiltonian

$$H_c = \hbar \chi_{cd} a^\dagger a \otimes |e\rangle\langle e|$$

where $$\chi_{cd}$$ denotes the dispersive coupling, and $$a^\dagger$$ and $$a$$ are the creation and the annihilation operators for the cavity mode. At interaction
time $\tau = \pi/\chi_{Q_0}$, this coupling leads to a qubit–state–dependent $\pi$–phase shift, $U = e^{i\phi_{1}(0)\sigma_{0}(\alpha)}$ (24–26). When the cavity is in the vacuum state $\left|0\right>$ (corresponding to the off state $\left|\alpha\right>$ of the WPD), the qubit state is not affected by the cavity coupling operator $U$. After the $\pi/2$ pulse $P_2$, the probability for recording the qubit in the state $\left|\alpha\right>$ is given by $P_\alpha = (1 - \cos \theta)/2$, which shows a perfect interference fringe with respect to the relative phase $\varphi$. However, if the cavity starts in a coherent state $|\alpha\rangle$ (corresponding to the on state $|0\rangle$ of the WPD), the coupling operator $U$ evolves the qubit-cavity system to the entangled state $(|\alpha\rangle + e^{i\varphi}|\alpha\rangle - |\alpha\rangle)/\sqrt{2}$. The probability for getting the qubit in the state $|\alpha\rangle$ after $P_2$ is given by $P_\alpha = (1 - e^{-2i\theta}\cos \varphi)/2$. When the overlap of the two labeling states $|\alpha\rangle$ and $|-\alpha\rangle$ is negligible, that is, $e^{-2i\theta} = 1$, the interference fringe disappears. In our experiment, the cavity is prepared in a superposition cat state

$$|\psi\rangle = \cos \theta |0\rangle + \sin \theta |\alpha\rangle$$

and the probability for recording the qubit in state $|\psi\rangle$ is given by

$$P_\psi = \left[ \cos^2 \theta (1 - \cos \varphi) + \sin^2 \theta /2 \right]$$

where the two terms of $P_\psi$ show the wave behavior (interference) and the particle behavior (no interference) of the superconducting qubit, respectively.

The experimental implementation is based on a three-dimensional (3D) circuit quantum electrodynamics (QED) architecture (see the Supplementary Materials for details) (27). The experiment starts with preparing the cavity in a coherent superposition of $|0\rangle$ and $|\alpha\rangle$, as in Eq. 3. The experimental pulse sequence (in fig. S1) and detailed description are presented in the Supplementary Materials. We experimentally generate these states with $\alpha = 2\sqrt{2}$. For $\theta = \pi/4$, the fidelity $F = \langle \psi | \rho | \psi \rangle = 0.93$, where $\rho_\psi$ is the density operator of the produced cavity state (measured Wigner function is shown in fig. S2). After creating the cat state, we sandwich the conditional $\pi$–phase shift gate $U$ between the two $\pi/2$ pulses $P_1$ and $P_2$ for the Ramsey interference measurement. In our experiment, the tunable phase shift $\varphi$ is incorporated into the first $\pi/2$ pulse $P_1$ by adjusting the phase of the corresponding microwave pulse. In Fig. 2 (A and B), we present the measured probability $P_\varphi$ as a function of $\varphi$ for different values of $\theta$. As expected, the qubit exhibits a continuous transition between wave- and particle-like behavior by varying $\theta$ that determines the initial state of the WPD.

**Verification of WPD’s quantum coherence**

The essence of quantum delayed-choice experiments is that the quantum coherence of the measuring device excludes the possibility of the qubit knowing the measurement choice in advance. To verify the presence of the quantum coherence between the on and off states of the WPD, we perform the Wigner tomography after the Ramsey interference experiment (24–26, 28). The Wigner function of a quantum harmonic oscillator, the quasi-probability distribution in phase space, contains all the information of the associated quantum state (29). In Fig. 3, we present the reconstructed state of the cavity without postselection on the qubit state (data conditional upon the qubit state $|\psi\rangle$ and $|\phi\rangle$ are presented in fig. S3) for $\theta = \pi/4$ and $\varphi = \pi/2$. As expected, the measured Wigner function (Fig. 3B) exhibits interference fringes, with alternate positive and negative values between 0 and $\alpha$ ($-\alpha$) in phase space, which are the signature of quantum coherence between $|0\rangle$ and $|\alpha\rangle$ ($-\alpha\rangle$). To further characterize this coherence, we display the density matrix (Fig. 3C) in the Hilbert space obtained from the measured Wigner function, where each term represents the modulus of the corresponding matrix element (without including the phase). The quantum coherence between $|0\rangle$ and $|\alpha\rangle$ ($-\alpha\rangle$) is manifested in the off-diagonal elements $[\rho_{0,\alpha}]$ and $[\rho_{\alpha,0}]$, which are responsible for the observed interference fringes in the Wigner function (24). These results unambiguously demonstrate that the qubit’s behaviors with and without interference are observed with the same setup, where the WPD is in a quantum superposition of its on and off states.

**Twofold delayed choice**

To postselect the qubit’s behavior, we examine whether the cavity is filled with a coherent field or is empty by using a conditional qubit rotation. Because of the dispersive qubit–cavity coupling, the qubit’s transition frequency depends on the photon number of the cavity field so that we can drive the qubit’s transition conditionally on the cavity being in a specific Fock state. After the Ramsey interference experiment, we perform a $\pi$ rotation on the qubit conditional on the cavity’s vacuum state

$$R_{+0}^{\pi} = \exp \left[ \frac{\pi}{2} \left|0\rangle\langle0| \otimes (|g\rangle - |g\rangle) \right] \right]$$

Because both $|\alpha\rangle$ and $|-\alpha\rangle$ are approximately orthogonal to $|0\rangle$, the qubit does not undergo transition for these two coherent state components. It should be noted that the coherent state $|\alpha\rangle$ is not distinguished from $|-\alpha\rangle$ after this procedure; that is, the which-path information is not read out. In Fig. 4A, we present the measured conditional probabilities $P_{g,O}^\psi$ and $P_{\overline{g},F}^\phi$ as functions of $\varphi$, which are defined as the probabilities for detecting the qubit in $|g\rangle$ in the Ramsey interference experiment conditional on the measurement of the WPD’s on state $|\alpha\rangle$ and off state $|0\rangle$, respectively. Here, the on and off states have equal weighting, that is, $\theta = \pi/4$. $P_{g,O}^\phi$ manifests the qubit’s interference behavior with a visibility of 0.89, whereas $P_{\overline{g},F}^\phi$ shows almost no
More intriguingly, the quantum erasure (plot the measured conditional probabilities postselected, resulting in the restoration of the fringes. In Fig. 4B, we even after the particle-like behavior (the red line of Fig. 4A) has been ability can be erased: When we measure the cavity coherence of the on and off states, as shown in Fig. 3, excludes any bandwidth of the function, and (Liu et al. 2017) –

The delayed-choice quantum eraser embedded in the quantum delayed-choice experiments (Liu et al. 2017) –

Because of the imperfection of the conditional π pulse (fig. S4G), there is a small probability that |0⟩ is taken for ±(|±a⟩); this accounts for the residual interference effects (with a fringe contrast of 0.04) in Pg;O. These results demonstrate that the qubit’s behavior depends on the WPD’s state; the quantum coherence of the on and off states, as shown in Fig. 3, excludes any model in which the choice corresponds to a classical variable that has been known in advance.

Unlike the previous quantum delayed-choice experiments (10, 12–17), here, the which-path information associated with the qubit’s particle-like behavior is not read out during the observation of the interference pattern; instead, it is stored in the field’s phase. This path distinguishability can be erased: When we measure the cavity’s parity, instead of distinguishing between |0⟩ and ±(|±a⟩), and correlating the outcomes with the qubit’s data, two complementary interference patterns appear (fig. S5). More intriguingly, the quantum erasure (18–23) can be realized even after the particle-like behavior (the red line of Fig. 4A) has been postselected, resulting in the restoration of the fringes. In Fig. 4B, we plot the measured conditional probabilities Pg;Oa and Pg;O−a as functions of φ, defined as the probabilities for measuring the qubit in |g⟩ after Pg conditional on the detection of even and odd parities of the WPD following the postselection of its on state, respectively. The fringe contrasts associated with Pg;O+ and Pg;O− are 0.53 and 0.48, respectively. The imperfection of these conditional interference patterns is mainly due to the infidelity of the π/2 pulses used for qubit Ramsey interference and WPD parity discrimination, which is predominantly caused by cavity photons.

On the other hand, if we choose to read out the which-path information by distinguishing between |a⟩ and |−a⟩, the qubit shows no interference, as shown in Fig. 4C, where Pg;Oa and Pg;O−a denote the probabilities to detect the state |g⟩ after Pg conditional on the postselection of the WPD’s on state and the subsequent measurements of |a⟩ and |−a⟩, respectively. These two states can be distinguished by successively performing the cavity displacement D(−a), the conditional qubit π rotation Rπ−a, and the qubit state measurement. We note that the thus obtained |−a⟩ state is mixed up with the residual vacuum, resulting in a slight oscillation in Pg;O−a with a contrast of 0.07. This fringe contrast can be further reduced by performing additional operations D(0) and Rπ0 and then measuring the qubit state to remove the residual vacuum. The deviation of Pg;O−a from 1/2 is mainly due to the qubit energy decay (see the Supplementary Materials).

The delayed-choice quantum eraser embedded in the quantum delayed-choice experiment is only enabled by using the quantum properties of the WPD, significantly extending the concept of delayed-choice experiment. The twofold delayed-choice procedure provides a clear demonstration that the behavior with or without interference is not a realistic property of the test system: It depends not only on the delayed choice of the WPD’s state but also on how we later measure the WPD and correlate the outcomes with the data of the test system.
DISCUSSION
In summary, we have proposed a twofold quantum delayed-choice experiment that is enabled by using a WPD prepared in a superposition of its on and off states. We implemented the experiment in circuit QED, observing both behaviors with and without interference for a superconducting qubit in the same experiment by using a cavity in a cat state as the WPD. We confirmed the existence of quantum coherences between the on and the off states of the WPD, excluding interpretations of the results based on classical models. The quantum properties of the WPD allow erasure of the which-path information associated with the postselected particle-like behavior, implementing the first twofold delayed-choice procedure. Our results show whether the qubit behaves as a wave or as a particle depends not only on the configuration of the measuring device, which can be chosen even after the qubit has been detected, but also on whether or not a posteriori erases or marks the which-path information, unambiguously demonstrating that the wave- or particle-like behavior of a quantum system is not a reality.

MATERIALS AND METHODS
Our experiment was implemented with a 3D circuit QED architecture (27), as shown in fig. S6, where a single transmon qubit in a waveguide trench was dispersively coupled to two 3D cavities (25, 26). One cavity served as the storage cavity, and the other was used to read out the qubit’s state. The transmon qubit was fabricated on a c-plane sapphire (Al2O3) substrate with a double-angle evaporation of aluminum after a single electron-beam lithography step. The qubit had a transition frequency ωq/2π = 5.577 GHz with an anharmonicity of ωq4/2π = (ω0e − ω0c)/2π = 246 MHz, an energy relaxation time of T1 = 9.5 μs, a Ramsey time of T2* = 7.5 μs, and a pure dephasing time of T2 = 12.4 μs.

Both the storage and readout cavities were made of aluminum alloy 6061 with a frequency of 8.229 and 7.292 GHz, respectively. The photon lifetimes in the storage and readout cavities were τs = 66 μs and τr = 44 ns, respectively. The dispersive coupling between the qubit and the storage (readout) cavity was χm/qr = π.64 MHz (χqr/2π = −4.71 MHz). The storage cavity acted as the WPD for the qubit in the Hilbert space. During the unitary evolution of the system combined by the qubit and the storage cavity, the readout cavity remained in the ground state, and we discarded it when describing the quantum state of the system.

The sample was placed in a cryogen-free dilution refrigerator at a base temperature of about 10 mK. Even at the lowest base temperature, the qubit was measured to have a probability about 8.5% of being populated in the excited state |e⟩ in the steady state. The exact source for this excitation is unknown; it may be caused by stray infrared photons or other background noise leaking into the cavity. This excitation can be removed through an initialization measurement of the qubit state by postselecting the projection of the system onto the ground state |g⟩ (see the Supplementary Materials) (30).

The schematic of the measurement setup is shown in fig. S7. We applied a Josephson parametric amplifier (JPA) (31, 32) operating in a double-pumped mode (red enclosed part in fig. S7 shows the biasing circuit) (33, 34) as the first stage of amplification between the readout cavity at base and the high-electron-mobility-transistor amplifier at 4 K. To minimize pump leakage into the readout cavity for a longer T2 time, we typically operated the JPA in a pulsed mode. This JPA allowed for a high-fidelity and quantum non-demolition single-shot readout of the qubit state (see section S3).

SUPPLEMENTARY MATERIALS
Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/3/5/e1603159/DC1

REFERENCES AND NOTES


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