Experimental observation of simultaneous wave and particle behavior in a narrowband single-photon wave packet

Hui Yan,[1,*] Kaiyu Liao,[1] Zhitao Deng,[1] Junyu He,[1] Zheng-Yuan Xue,[1] Zhi-Ming Zhang,[2] and Shi-Liang Zhu[3,1,4,†]

[1]*Guangdong Provincial Key Laboratory of Quantum Engineering and Quantum Materials, School of Physics and Telecommunication Engineering, South China Normal University, Guangzhou 510006, China*

[2]*Guangdong Provincial Key Laboratory of Quantum Engineering and Quantum Materials, School of Information and Photoelectronic Science and Engineering, South China Normal University, Guangzhou 510006, China*

[3]*National Laboratory of Solid State Microstructures, School of Physics, Nanjing University, Nanjing 210093, China*

[4]*Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei 230026, China*

Light's wave-particle duality is at the heart of quantum mechanics and can be well illustrated by Wheeler's delayed-choice experiment: The choice of inserting or removing the second classical (quantum) beam splitter in a Mach-Zehnder interferometer determines the classical (quantum) wave-particle behavior of a photon. In this paper, we report our experiment on directly observing simultaneous wave and particle behavior in a narrowband single-photon wave packet by classically inserting or removing the second beam splitter when part of the wave packet passes through it. Our experiment demonstrates that the produced wave-particle state can be utilized in encoding quantum information.

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I. INTRODUCTION

The dual wave-particle (WP) nature of light has been debated for centuries [1,2]. In order to test the WP duality, Wheeler proposed the famous delayed-choice gedanken experiment [3,4]. The main experimental setup is a Mach-Zehnder interferometer. After a photon passes through the first beam splitter (BS), the choice of inserting or removing the second BS is then randomly determined. If the second BS is present, the photon travels through both beams of the Mach-Zehnder interferometer and interference fringes can be observed, indicating the wave behavior of the photon. If the second BS is absent, the photon randomly travels through one beam of the Mach-Zehnder interferometer and only one of the two output ports has a click, showing the full "which-path" information and the particle properties of the photon.

Since Wheeler's proposal, many delayed-choice experiments have been realized [5–13]. Depending on the measurement setup (here it is the second BS), these experiments can be categorized as either classical or quantum types. If the measurement setup is classical (that is, the second BS can be either present or absent, but cannot be both present and absent simultaneously), the experimental results [5–10] support Bohr's original complementary principle [2], which is also called the classical WP duality. It states that a photon may behave either as a particle or a wave, depending on the measurement setup, but the two aspects, particle and wave, appear to be incompatible and are never observed simultaneously.

Very recently, Ionicioiu and Terno proposed a quantum version of the above delayed-choice experiment, in which the second BS in the Mach-Zehnder interferometer is a quantum BS. In other words, the second BS can be simultaneously present and absent [14,15]. In this case a continuous morphing behavior between the wave and particle is expected. Soon after, several experiments were conducted, and their results confirm the morphing behavior between WP [11–13]. These experiments suggest that a naive "wave or particle" description (i.e., the classical WP duality) of light is inadequate and the generalization to a quantum version is necessary. The quantum version of WP duality states that light exhibits particlelike or wavelike behavior depending on the experimental apparatus: With a quantum detecting setup, light can simultaneously behave as a particle and as a wave, whereas with a classical setup, light behaves as a particle or as a wave [11]. In the above classical and quantum versions of the WP duality, the wave and particle states are still very special. We may ask a further important question: Can we create a superposition state of the WP, and then observe simultaneous wave and particle behavior with a classical detecting setup?

In this paper, by using heralded narrowband single photons, we experimentally observe the quantum WP behaviors using a classical setup, the same detection setup used in Ref. [10] to realize Wheeler's classical delayed-choice experiment. Benefiting from a long temporal length, we simultaneously and directly observe the wave and particle behaviors in a narrowband single-photon wave packet by classically inserting or removing the second BS when part of the wave packet passes through the second BS. Therefore, our results answer the above question: One can create the superposition state of the wave and particle, and then observe its quantum behaviors with a classical detecting setup. Interestingly, the approach developed in our experiment is a convenient way to manipulate the WP state, which has an exciting potential given that the WP superposition state can be used as a dual-rail qubit for quantum information processing [16,17]. Therefore our work will not only be useful for understanding the WP duality and Bohr's complementarity principle, but also opens up the possibility of directly using the WP state in encoding information.

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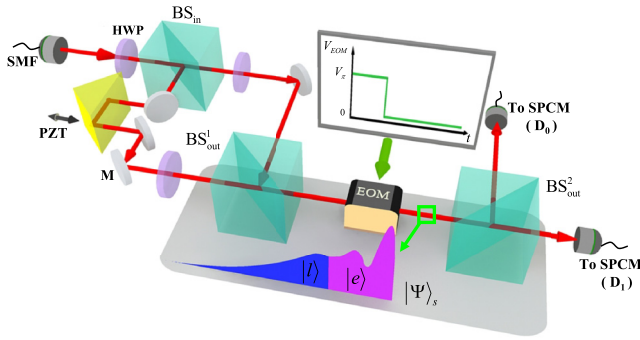*yanhui@scnu.edu.cn

†slzhu@nju.edu.cn

FIG. 1. (Color online) Experiment setup. The main setup is a polarization beam splitter (BS) enabled Mach-Zehnder interferometer. A photon is split by BS_{in} into two modes with different orthogonal polarizations and then spatially recombined by BS_{out}^1. An electro-optical modulator (EOM) is used as a controllable half-wave plate. BS_{out}^2, positioned after the EOM, is used to mix the two orthogonal polarizations or split the two modes. When V_π voltage is applied to the EOM, the interference configuration is closed and the interference fringe will be detected at the two output ports. When no voltage is applied, the interferometer configuration is open, and each of the two output ports provides the full "which-path" information. M: mirror; SMF: single-mode fiber; HWP: half-wave plate; SPCM: single-photon count module; PZT: piezoelectric transducer; $D_{0,1}$: detectors; $|e\rangle$, $|l\rangle$: time-bin degree states; $|\Psi\rangle_s$: single-photon wave function.

II. EXPERIMENTAL SETUP AND THEORETICAL DESCRIPTION

Our experimental setup is shown in Fig. 1. A heralded narrowband single photon with a coherence time τ around 400 ns [18–23] is sent through a polarization BS enabled Mach-Zehnder interferometer. Narrowband photon pairs generated through spontaneous four-wave mixing and a slow light technique with cold atoms are utilized to produce the heralded narrowband single photons [18,24] used in our experiment. The source, which has been described in our previous papers [23,25], is run periodically with a magneto-optical trap for a trapping time of 4.5 ms and a biphoton generation time of 0.5 ms. The neutral ^{85}Rb atoms with an optical depth of 45 are trapped in 4.5 ms. A four-energy-level double-Λ system is chosen for the spontaneous four-wave mixing. In the presence of the pump ($I_p \sim 50~\mu$W) and coupling lasers ($I_c \sim 1.6$ mW), the counterpropagating Stokes and anti-Stokes photons are generated into opposite directions. The detection of one Stokes photon, which also determines the starting point of the experiment, heralds the generation of one narrowband single photon (anti-Stokes photon). The biphoton generation rate is 47 230 s^{-1} after taking into account all of the losses. The normalized cross-correlation function $g_{s,as}^{(2)}(\tau)$ between the Stokes and anti-Stokes photons is around 39, which indicates the violation of the Cauchy-Schwartz inequality by a factor of 381. The related conditional second-order correlation of the heralded single photon $g_c^{(2)} = 0.23 \pm 0.05$, which indicates a real single photon. The photon guided by a single-mode fiber from the source is equally split by BS_{in} into two spatially separated paths $|0\rangle$ and $|1\rangle$ associated with orthogonal polarizations. Then the initial photon state becomes the superposition $(|0\rangle + |1\rangle)/\sqrt{2}$. The phase shift φ between the

two interferometer arms is varied by a piezoelectric transducer, resulting in the state $|\Psi\rangle = (|0\rangle + e^{i\varphi}|1\rangle)/\sqrt{2}$. Both modes are then recombined on a second controllable BS_{out}. In our experimental setup shown in Fig. 1, two polarization beam splitters (BS_{out}^1 and BS_{out}^2) and an electro-optical modulator (EOM, Newport Model 4102NF) are combined into a controllable BS_{out} [10]. BS_{out}^1 combines the two beams in the Mach-Zehnder interferometer in space, but they can still be identified by their polarizations. The EOM is used as a controllable half-wave plate. The axis of the EOM is aligned 25.5° to the input polarizations. When V_π is applied to the EOM, the EOM is equivalent to a half-wave plate and can rotate the input polarization state (horizontal and vertical) by 45°. In this case, BS_{out}^2 after the EOM can mix the two orthogonal polarizations and erase the path information. This condition occurs when the controllable BS_{out} is present and the interferometer is closed. When $V = 0$ is applied to the EOM, the EOM has no effect on the input polarization state. In this case, BS_{out}^2 is simply used to split the two orthogonal polarizations and the path information is kept. This condition occurs when the controllable BS_{out} is absent and the interferometer is open. The EOM voltage between $V_\pi = 198$ V and $V = 0$ can be switched via a fast metal-oxide-semiconductor field-effect transistor (MOSFET) (Infineon: BSC16DN25NS3) with a switch-off speed of faster than 15 ns. Compared with the total 400 ns temporal length of the single photon, the maximum influence of the switch-off process to the test probability is less than 0.04. The insertion or removal of this controllable "BS_{out}" is determined when part of the narrowband photon wave packet passes through.

Because of the long temporal coherent length of the single narrowband photon, the time-bin degree of freedom can be well manipulated and the time-bin information can be easily detected [26–28]. We can split the photon into the time-bin superposition $|\psi\rangle = \cos\alpha|e\rangle + e^{i\gamma}\sin\alpha|l\rangle$, where $|e\rangle$ ($|l\rangle$) is the early (late) time bin. The two modes are first overlapped by BS_{out}^1 but can still be identified by their polarization. Then the choice between a closed or open interferometer configuration is achieved with the EOM: Either no voltage or V_π voltage is applied to the EOM. In our experiment, V_π is applied to the EOM at the early time bin. Therefore, the BS_{out} is present and the interferometer is closed at the $|e\rangle$ time slot. In this case, the statistics of measurements at both detectors D_0 and D_1 will depend on the phase φ, which will reveal the wave nature of the photon. Thus the photon is in the "wave" state given by

$$|\Psi\rangle_w = |e\rangle \otimes |\psi\rangle_w, \quad |\psi\rangle_w = \cos\frac{\varphi}{2}|0\rangle - i\sin\frac{\varphi}{2}|1\rangle. \quad (1)$$

On the other hand, no voltage is applied at the late time bin and thus the controllable BS_{out} is not present for the $|l\rangle$ time slot; hence, the interferometer is left open. In this case, both detectors will click with equal probability, which will reveal the particle nature of the photon. The photon is in the "particle" state given by

$$|\Psi\rangle_p = |l\rangle \otimes |\psi\rangle_p, \quad |\psi\rangle_p = \frac{1}{\sqrt{2}}(|0\rangle + e^{i\varphi}|1\rangle). \quad (2)$$

Therefore, the main feature of the EOM is that it can split the single photon into two time bins and further entangle the time-bin degree of freedom with the WP state. For the superposition state in the time-bin degree, the global state $|\Psi\rangle_s$ of the system
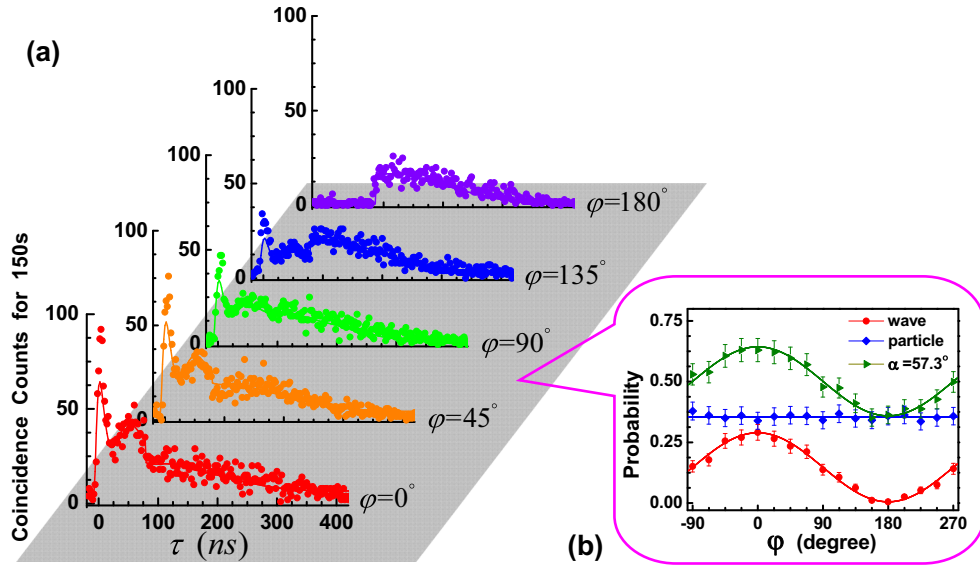
FIG. 2. (Color online) Temporal wave packet of the single photon measured through coincidence counts. (a) The total temporal length of the single photon is about 400 ns. During the first 80 ns, the voltage V_π is applied to the EOM, and a clear interference fringe is observed along with the change of the phase difference φ from $0°$ to $180°$. After 80 ns, no voltage is applied to the EOM, and the coincidence counts remain stable with different φ. (b) Probability of detecting a photon with D_0 during different time slots. The red line with solid circles stands for 0–80 ns. The blue line with prismatic plots stands for 80–400 ns. The green line with triangular plots stands for 0–400 ns. For both (a) and (b), the plots and lines are experimental data and theoretically predictions, respectively.

after the EOM becomes

$$|\Psi\rangle_s(\alpha,\varphi,\gamma) = \cos\alpha|\Psi\rangle_w + e^{i\gamma}\sin\alpha|\Psi\rangle_p. \qquad (3)$$

After BS_out^2, we measure the photon state, and the probability of detecting the photon at detector D_0 is then given by

$$I_{D_0}(\alpha,\varphi) = \cos^2\left(\frac{\varphi}{2}\right)\cos^2\alpha + \frac{1}{2}\sin^2\alpha, \qquad (4)$$

whereas intensity at D_1 is $I_{D_1} = 1 - I_{D_0}$.

It seems that the experimental setup shown in Fig. 1 is the same as that in the classical delayed-choice experiment [10]; the statistics are quite different, which should be explained with the WP superposition state as in the quantum delayed-choice experiment [14]. Compared with the experiment in Ref. [10], the main difference in our experiment is that a heralded single photon with a long temporal length is used, thus the single photon can have three degree of freedoms: time bin, WP, and polarization. Furthermore, the time-bin states $|e\rangle$ and $|l\rangle$ are entangled with the WP state $|\psi\rangle_w$ and $|\psi\rangle_p$. Hence, by choosing the proper measurement basis (different time slots for $|e\rangle$ and $|l\rangle$) which can be controlled by EOM, we can demonstrate the quantum character of the WP duality in this classical setup according to the above theoretical analysis.

III. EXPERIMENTAL RESULTS

As a typical example of the experimental results, the BS_out is present before 80 ns and then removed at 80 ns. In this case, the α in Eq. (3) is about $57.3°$, which is determined by the ratio of the coincidence counts for 0–80 ns ($|e\rangle$) and 80–400 ns ($|l\rangle$). The measured coincidence counts (time bin

1 ns) at D_0 is shown in Fig. 2(a), where φ are altered from $0°$ to $180°$. Before BS_out is removed (0–80 ns), an interference fringe determined by φ is observed, which clearly reveals the wave nature of the photon. After BS_out is removed (80–400 ns), coincidence counts remain stable for all φ since only one path could be detected by D_0, which exhibits the "which-path" information and reveals the particle nature of the photon. These results are in excellent agreement with theoretical predictions. More interestingly, the temporal wave packet of a single photon shown in Fig. 2(a) demonstrates the simultaneous WP behavior. Here, we directly observe the simultaneous wave and particle behaviors in the same temporal wave packet, which will shed light on further understanding of the WP duality.

The produced WP supposition state can be further analyzed by choosing different measurement bases in the time-bin degree. As shown in Fig. 2(b), in which data are extracted from Fig. 2(a), if $|e\rangle$ is chosen as the basis, a perfect interferometer fringe is obtained (red solid circles and line), and the interference visibility, defined as the ratio of the oscillation amplitude to the sum of the maximum and minimum probabilities, is 0.968. If $|l\rangle$ is chosen as the basis, a straight line is obtained (blue prisms and line), and the visibility is 0.043. If $|e\rangle + |l\rangle$ is chosen as the basis, a WP superposition can be obtained, and the interference fringe is still observable but with a smaller visibility of 0.306 (green triangles and line). Therefore, Fig. 2(b) clearly demonstrates that the visibility in the pure wave (particle) state is almost one (zero), whereas in the intermediate cases, the visibility reduces but does not vanish. This result fits very well with the theoretical prediction and has been observed in the quantum delayed-choice experiments [11].
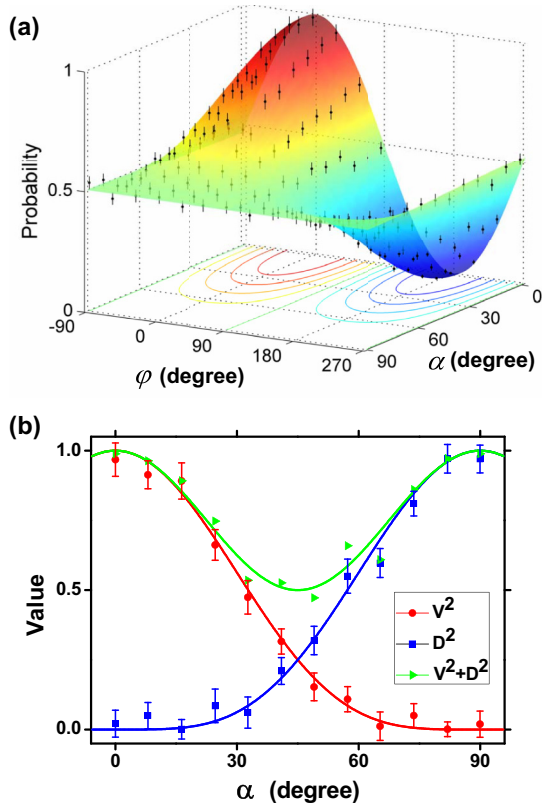
FIG. 3. (Color online) Characterization of the continuous transition between WP behaviors. (a) The probability of detecting a photon at D_0 as a function of the angles α and φ. Dots and error bars represent experimental data points and their corresponding standard deviations. The experimental data are fitted by using Eq. (4) and show excellent agreement with theoretical predictions. (b) Plots and related fits (solid lines) of the fringe visibility V^2 (red solid circles) and path distinguishability D^2 (blue squares) as a function of the angle α. For all angles α, the inequality $V^2 + D^2 \leqslant 1$ is verified.

In order to further study the features of the above WP superposition state, we measure the entire coincidence counts at D_0 and then normalized (I_{D_0}) for $\alpha \in [0,90°]$ and $\varphi \in [-90°,270°]$. As shown in Fig. 3(a), the experimentally measured results are in excellent agreement with the theoretical predictions of Eq. (4). For the angle $\alpha = 0°$, a perfect interference fringe with a visibility around one is shown as a function of φ, which corresponds to wavelike behavior. For $\alpha = 90°$, the measured $I_{D_0} = 1/2$ and is independent of φ, which shows particlelike behavior. For $0° < \alpha < 90°$, a continuous transition from wave to particle behavior is observed, which is expressed by the continually reducing fringe visibility.

As outlined in Refs. [29–33], a generalized Bohr's complementarity principle supports the simultaneous observation of the WP behavior, but the total wavelike and particlelike information (interference fringe visibility V and path distinguishability D) should be limited by the Englert-Greenberger inequality $V^2 + D^2 \leqslant 1$. In our experiment, V can be obtained from the data shown in Fig. 3(a), whereas $D = \frac{|N_1 - N_2|}{N_1 + N_2}$ should be measured by blocking one of the beams in the

Mach-Zehnder interferometer [32]. Here, N_1 is the total counts on $D_0(D_1)$ by blocking one of the beams, and N_2 is also the total counts on $D_0(D_1)$ by blocking the other beam. The results are shown in Fig. 3(b): $V^2 + D^2 < 1$ when $0° < \alpha < 90°$, and $V^2 + D^2 = 1$ only when $\alpha = 0°$ or $90°$. These results fit very well with the theoretical predictions and fulfill the Englert-Greenberger inequality for all angles of α.

Since the quantum behaviors as shown in Figs. 2 and 3 are clearly observed with the classical detecting setup in our experiment, this observation may bring a different meaning to the concept of wave-particle duality. Taking a spin half particle as an example, one can create a superposition state of spin up and down, and then observe the quantum behaviors of spin up and down with a classical measurement setup. Similarly, by employing the language used by Ionicioiu and Terno [14], one can write the wave function of a photon's wave or particle state, as well as the superposition state of them. By taking advantage of the long temporal coherent length of the narrowband single photon, we create such a superposition state of the WP, and thus it is a reasonable result that we can observe the simultaneous WP behaviors with a properly designed classical measurement setup.

IV. DISCUSSION AND CONCLUSIONS

Here, we briefly address that the approach developed in our experiment is a convenient way to manipulate the WP state, which has exciting potentials given that the WP superposition state can be used as a qubit for quantum information processing [16]. In addition to that, the parameters α and φ in Eq. (3) are controllable in our experiment, and the phase γ in Eq. (3) can be manipulated, too. By adding another EOM after the existing EOM, the phase γ between the WP states can be tunable. In addition, with another unequal arm Mach-Zehnder interferometer, the time-bin information can be erased and the phase γ can be measured. Furthermore, by adding a $\lambda/4$ wave plate after the EOM, the WP supposition can be reversed to $|\Psi\rangle_s(\alpha,\varphi,\gamma) = \cos\alpha|e\rangle|\psi\rangle_p + e^{i\gamma}\sin\alpha|l\rangle|\psi\rangle_w$.

In conclusion, we have observed the quantum WP behavior in a single-photon wave packet with the insertion or removal of the second BS through a classical setup. The utilization of a narrowband single photon enables us to observe the WP supposition state, as shown in quantum delayed-choice experiments but with a classical detecting setup. Our experiment can also provide a feasible way to create a WP superposition state, which could be useful in quantum information processing.

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