Simple implementation of quantum delayed-choice experiment using conventional linear optical elements

Qi Guo, 1 Liu-Yong Cheng, 1 Hong-Fu Wang, 2 and Shou Zhang* 1, 2

1Department of Physics, Harbin Institute of Technology, Harbin, Heilongjiang 150001, People’s Republic of China

2Department of Physics, College of Science, Yanbian University, Yanji, Jilin 133002, People’s Republic of China

We propose a simple implementation scheme of quantum delayed-choice experiment in linear optical system without initial entanglement resource. By choosing different detecting devices, one can selectively observe the photon’s different behaviors after the photon has been passed the Mach-Zehnder interferometer. The scheme shows that the photon’s wave behavior and particle behavior can be observed with a single experimental setup by postselection, that is, the photon can show the superposition behavior of wave and particle. Especially, we compare the wave-particle superposition behavior and the wave-particle mixture behavior in detail, and find the quantum interference effect between wave and particle behavior, which may be helpful to reveal the nature of photon essentially.

Keywords: Quantum delayed-choice experiment; Linear Optics; wave-particle duality

I. INTRODUCTION

For centuries, scientists have always debated whether the light is particle or wave. Now it is well accepted that light is both particle and wave, that is, wave-particle duality. However, Bohr’s principle of complementarity [1] shows that no experiment can measure both the wave and the particle behaviors simultaneously, which plays an important role in quantum physics. Mach-Zehnder interferometer (MZI) is an effective tool for verifying wave-particle duality, because when light passes through MZI, one can obtain interference pattern in both of the

* E-mail: szhang@ybu.edu.cn
outputs of the MZI, and the light behaves as wave. While, if the second beam splitter (BS) (or say output BS) of the MZI is removed, we’ll know the explicit which-path information of photons and can’t obtain interference pattern in the outputs, so the light behaves as particle. However, another objection is that maybe photons somehow know whether the second BS is removed or not in advance, so they can adjust themselves to the corresponding device. In order to test this conjecture, Wheeler proposed a famous thought experiment, i.e. delayed-choice experiment \[2, 3\]. In this experiment, observers can decide to observe the wave or particle behavior of a photon after it passed the first BS of a MZI by inserting or removing the second BS, so that the photon can’t know what measuring devices lie ahead before it is emitted. This gedanken experiment has attracted great attention \[4–7\]. With the development of experimental technology, some interesting thought experiments can be realized in current laboratory. Jacques et al. performed Wheeler’s delayed-choice experiment with optical interferometer \[8\] and tested quantum complementarity with interfering single photons \[9\].

In 2011, Ionicioiu et al. presented a quantum version delayed-choice experiment by replacing the second BS with a quantum-controlled BS (q-BS) \[10\], which could delay the choice of observers until the photon left the MZI. This is a significant progress from classical control to quantum control, so it has attracted the attention of many researchers and some experimental realizations have been completed in different physical systems \[11–16\]. These works amply demonstrated the validity of the quantum delayed-choice experiment and provided effective methods for testing the particle and wave behaviors of photons. In addition, quantum delayed-choice experiment opens the probability for generating photon’s wave-particle superposition state, in other words, quantum delayed-choice experiment allows wave and particle behavior to be observed simultaneously in a single experimental setup. Inspired by Ref. \[15\], we here present a simple implementation scheme of quantum delayed-choice experiment by using the commonest linear optical elements without initial entangled photon pairs. By choosing corresponding detecting device after the photon left the MZI, one can selectively observe photon’s wave behavior, particle behavior, wave-particle mixture behavior and wave-particle superposition behavior. they only observed the statistical mixture of wave and particle behavior. More importantly, we show the genuine superposition behavior of wave and particle state, and compare it with the wave-particle mixture behavior revealed in the existing theoretical and experimental works.
II. QUANTUM VERSION OF DELAYED-CHOICE EXPERIMENT

Now we briefly review the quantum delayed-choice experiment. The main difference between quantum and classical delayed-choice experiment is that the second BS of the MZI is replaced by a quantum-controlled BS in the former, which means the presence or absence of the second BS is controlled by a quantum superposition state rather than a experimenter or a classical random number generator [10]. For simplicity, we explain the quantum delayed-choice experiment with Fig. 1(a). The input photon is in the superposition state of horizontal and vertical polarization, i.e. $|\varphi\rangle = \sin \alpha |H\rangle + \cos \alpha |V\rangle$, $|H\rangle$ and $|V\rangle$ denote the horizontal and vertical polarization state of the photon, respectively. The two paths of the MZI express as $|0\rangle$ and $|1\rangle$. Here, q-BS is a polarization-dependent BS, which can completely transmit vertically polarized photons and 50/50 split horizontally polarized photons (the realization of q-BS will be introduce in the next section). Therefore, a vertically polarized photon passes one path and exhibits particle behavior, but an horizontally polarized photon passes both of two paths and exhibits wave behavior. If we consider the polarization and path degree of freedom as control and target qubit, respectively, the equivalent quantum circuit diagram of Fig. 1(a) can be represented as Fig. 1(b). $\theta$ is a single-qubit gate $U(\theta) = \text{diag}(1, e^{i\theta})$. The detector $D_c$ can distinguish the control qubits $|0\rangle$ and $|1\rangle$ (here $|0\rangle \equiv |V\rangle$ and $|1\rangle \equiv |H\rangle$), and $D_t$ represents the device of detecting the particle or wave behavior of the photon, which means the devices contains not only the photon detectors but also the analysis procedure of the coincidence count probabilities after the detecting.

In original Wheeler’s delayed-choice experiment, the decision of inserting the second BS or not must be made after the photon passes the first BS and before it reaches the second BS. However, this temporal arrangement is not necessary anymore in the quantum delayed-choice experiment. For the initial state $|\phi\rangle = (\cos \alpha |0\rangle + \sin \alpha |1\rangle)|0\rangle$, the control qubit of Fig. 1(b) will be entangled with the behavior of the input photon after passing through the quantum network, which can be expressed as

$$|\phi^\prime\rangle = \cos \alpha |0\rangle |\text{particle}\rangle + \sin \alpha |1\rangle |\text{wave}\rangle,$$

where $|\text{particle}\rangle = \frac{1}{\sqrt{2}} (|0\rangle + e^{i\theta}|1\rangle)$ and $|\text{wave}\rangle = e^{i\theta/2} (\cos \frac{\theta}{2} |0\rangle - i \sin \frac{\theta}{2} |1\rangle)$ represent the particle and wave behavior, respectively. Therefore, the detection results of $D_c$ and $D_t$ necessarily relate to each other. If we know one of the two detection devices’ results, the state of Eq. (1) will collapse and the result of the other detecting device will be immediately
FIG. 1: (a) Schematic of the quantum delayed-choice experiment. BS is a beam splitter. $\theta$ is the relative phase difference between the two paths. q-BS is quantum BS, which means the second BS is inserted for horizontally polarized photons and removed for vertically polarized photons. $D_1$ and $D_2$ are photon detectors. (b) The equivalent quantum circuit diagram of (a). The control qubit is served as by the polarization degree of freedom of the photon in (a). $H$ denotes Hadamard conversion. $D_c$ can distinguish the states of the control qubit $|0\rangle$ and $|1\rangle$, and $D_t$ is the device of detecting the particle or wave behavior of the photon.

determined even without working. Hence, the choice of observing a photon’s wave or particle behavior can be delayed to the future light cone of the event that the photon leaves the MZI, and can’t be made in the past light cone of the detection of the photon.

III. IMPLEMENTATION SCHEME AND WAVE-PARTICLE SUPERPOSITION

In Fig. 2, we show how to simply realize quantum delayed-choice experiment with ordinary optical elements. Compared with the existing works, our scheme is simpler and doesn’t need initial entanglement resource. Moreover, we will research the genuine superposition behavior of wave and particle state, and clearly compare it with the classical mixture of wave and particle behaviors.

The initial photon is in the polarization superposition state $|\psi\rangle = \sin \alpha |H\rangle + \cos \alpha |V\rangle$. The two paths also express as $|0\rangle$ and $|1\rangle$, respectively. Let the photon enter the setup from path 0. After the photon passes though the PBS$_3$ and PBS$_4$, the final state can be expressed with both the path degree of freedom and the polarization degree of freedom

$$|\psi'\rangle = \cos \alpha |\text{particle}\rangle |V\rangle + \sin \alpha |\text{wave}\rangle |H\rangle,$$

(2)

where $|\text{particle}\rangle$ and $|\text{wave}\rangle$ are the same as Eq. (1). Equation (2) actually is a single photon path-polarization hyperentangled state. Then we can detect different behaviors of the photon
FIG. 2: The implementation setup for quantum delayed-choice experiment. $|\psi\rangle = \sin \alpha |H\rangle + \cos \alpha |V\rangle$. BS: beam splitter. 0 and 1 indicate the two paths of the MZI. PBS: polarization beam splitter. $\theta$: adjustable phase shifter. HWP: half wave plate oriented at 22.5°. D$_i$: photon detector. If the device in rounded rectangle is removed, the detectors D$_2$ and D$_3$ will detect the classical mixture of wave and particle behavior. If the device in rounded rectangle is inserted, D$_1$ and D$_4$ (D$_2$ and D$_3$) will detect superposition behavior of wave and particle state, but when we remove the HWPs, D$_1$ and D$_4$ (D$_2$ and D$_3$) will detect particle (wave) behavior respectively.

by choosing different detection devices. If we remove the two HWPs in Fig. 2, obviously, D$_1$ and D$_4$ detect the particle behavior, whose probabilities of detecting photon are $I_1 = I_4 = \frac{1}{2}$, resulting in the visibility of the interference pattern is $V_1 = V_4 = (I_{max} - I_{min})/(I_{max} + I_{min}) = 0$. And D$_2$ and D$_3$ detect the wave behavior, so the detecting probabilities of D$_2$ and D$_3$ are $I_2 = \cos^2 \frac{\theta}{2}$ and $I_3 = \sin^2 \frac{\theta}{2}$, respectively, resulting in the visibility $V_2 = V_3 = 1$. If we remove the device in rounded rectangle of Fig. 2 and directly detect the photon in the two paths with D$_2$ and D$_3$, we can obtain the mixture state of particle and wave

$$\rho = \text{Tr}_{pol} |\psi'\rangle \langle \psi'| = \cos^2 \alpha |\text{particle}\rangle \langle \text{particle}| + \sin^2 \alpha |\text{wave}\rangle \langle \text{wave}|,$$

which is the reduced density matrix tracing out the polarization qubit for Eq. (2). Take D$_2$ for example, the probability that D$_2$ detects photon (or interference pattern) for the mixture state is

$$I_0(\theta, \alpha) = \text{Tr}[\rho|0\rangle \langle 0|] = \cos^2 \frac{\theta}{2} \sin^2 \alpha + \frac{1}{2} \cos^2 \alpha.$$  (4)

We plot the graph of the above probability distribution function $I_0(\theta, \alpha)$ as shown in Fig. 3(a). It’s easy to see that Fig. 3(a) is the same as the previous works in Refs. [10,14,15],
which indicates the wave-particle mixture state has been revealed and experimental results fitted well with theoretical predictions.

We think it is important to study the intermediate behavior between wave and particle for revealing the nature of photon essentially. For this purpose, it firstly should be required to prepare the pure superposition state of wave and particle. Now, we insert the device in rounded rectangle of Fig. 2. to research the genuine superposition behavior of wave and particle state. After the photon passes through the HWPs, the photon state will be involved as

\[ |\psi'\rangle = \frac{1}{\sqrt{2}}[(\cos \alpha |\text{particle}\rangle + \sin \alpha |\text{wave}\rangle)|H\rangle - (\cos \alpha |\text{particle}\rangle - \sin \alpha |\text{wave}\rangle)|V\rangle]. \quad (5) \]

Hence D₁ and D₄ (D₂ and D₃) will detect wave-particle superposition state \( \cos \alpha |\text{particle}\rangle - \sin \alpha |\text{wave}\rangle \) (\( \cos \alpha |\text{particle}\rangle + \sin \alpha |\text{wave}\rangle \))(not normalized). And we can obtain pure wave-particle superposition by postselection. Take D₂ and D₃ for example, the normalized wave-particle superposition state obtained in these outputs is accurately expressed as

\[ |\phi\rangle = \frac{1}{\sqrt{1 + \sqrt{2}\sin \alpha \cos \alpha \cos \theta}}(\cos \alpha |\text{particle}\rangle + \sin \alpha |\text{wave}\rangle). \quad (6) \]

For this state, we can theoretically derive the coincidence count probability (or interference pattern) of path 0 (detector D₂),

\[ I'_0(\theta, \alpha) = \frac{1 + \sin^2 \alpha \cos \theta + \sqrt{2}\sin 2\alpha \cos^2 \frac{\theta}{2}}{2 + \sqrt{2}\sin 2\alpha \cos \theta}, \quad (7) \]

which is very different from the probability of mixed states in Eq. (4). In order to distinctly compare them, we plot the probability distribution \( I'_0(\theta, \alpha) \) as shown in Fig. 3(b). Comparing with Fig. 3(a), Fig. 3(b) is more unimaginable, which should be the essential behavior of a photon and shows the genuine morphing behavior between wave and particle. The only overlap between the two cases is that when \( \alpha = 0 \) and \( \frac{\pi}{2} \), both of the two graphs correspond to particle-like and wave-like behaviors, respectively. In particular, it is worth to note that when \( \alpha = \frac{\pi}{4} \), the photon is in the superposition state \( |\psi\rangle = \frac{1}{\sqrt{1 + \sqrt{2}\cos \theta}}(|\text{particle}\rangle + |\text{wave}\rangle) \), but the probability distribution is a horizontal straight line and doesn’t change with phase shift \( \theta \) in Fig. 3(b). Theoretically, when \( \alpha \) takes values \((2n+\frac{1}{4})\pi\) and \((2n+\frac{3}{4})\pi\), \( n = 0, 1, 2... \), \( I'_0(\theta) \) will equal to \( \frac{1}{4}(2 + \sqrt{2}) \) and \( \frac{1}{4}(2 - \sqrt{2}) \), respectively. In this case, the visibility \( V = 0 \), and the photon is in the wave-particle superposition state but only shows the particle-like behavior, which is the quantum interference effect resulting from the coherence between wave and particle.
Fig. 3: Plots of the probability distributions of the photon in path 0 (detector D$_2$) of the Fig. 2. For clarity, we choose $0 < \theta < 5\pi$. (a) shows the mixture behavior of wave and particle, as defined by Eq. (4), $I_0(\theta, \alpha)$. (a) is the same as the Fig. 3(A) and (B) in Ref. [14], Fig. 2 in Ref. [10], and Fig. 4(A) and (C) in Ref. [15]. (b) is the genuine wave-particle superposition behavior, as defined by Eq. (7), $I'_0(\theta, \alpha)$. Because of the coherent quantum superposition of wave and particle state, (b) shows more specific phenomenon than (a) due to the coherent quantum superposition of wave and particle state.
IV. DISCUSSION AND CONCLUSION

So far, we have analyzed the quantum delayed-choice experiment in detail and pointed out that experimenter can observe which behavior photon exhibits as soon as it is detected by a detector, while the photon still doesn’t know if it is supposed to be a wave or a particle. Based on the basic idea of quantum delayed-choice experiment, we have proposed a simper linear optical scheme for realizing quantum delayed-choice experiment, which only requires the most common optical elements in optics laboratory[17, 18], such as BS, PBS, phase shifter, and HWP. Hence the present scheme can be easily realized under the current experimental condition. The scheme allowed us to selectively observe the wave-particle mixture or superposition behavior by choosing different detection device. In addition, quantum delayed-choice experiment allows wave behavior and particle behavior to be observed with a single experimental setup by postselection, and most of previous works has studied the wave-particle mixture behavior. In this paper, we can see wave-particle mixture behavior is very different from the superposition behavior, which may be more closed to the photon’s essential behavior and needed to be test experimentally in the future.

In conclusion, we have proposed a simple realizable implementation scheme of quantum delayed-choice experiment without initial entangled resource, which can be used for selectively observing different behaviors of photons. And the genuine wave-particle superposition behavior has been shown for the first time in this paper. Especially, we have explicitly compared the wave-particle mixture behavior with the wave-particle superposition behavior and found the quantum interference effect between wave and particle behavior, which may be meaningful to reveal the nature of photon essentially.

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