Delayed-choice quantum erasure using Poisson-distributed photons

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***Abstract*— Quantum superposition lies at the core of quantum mechanics and has been applied to various quantum technologies. Over the past few decades, Wheeler's delayed-choice thought experiment has been extensively examined to explore the wave-particle duality of the complementary nature of quantum mechanics. The essence of the delayed-choice quantum eraser lies in the contradictory quantum property that violates the cause-effect relationship in classical physics. Our experiments present empirical evidence of the quantum eraser using coherent photon pairs provided in a noninteracting Mach-Zehnder interferometer for the polarization-basis control of output photons. The observed interference fringe is the direct proof of the quantum eraser, where the violation of the cause-effect relationship is due to the selective choices of the measurement events.**

Keywords—wave-particle duality, complementarity theory, self-interference, delayed-choice, quantum eraser, attenuated coherent photons

I. Introduction

Quantum mechanics, with its intriguing principles of superposition and entanglement, has challenged our classical intuitions about the nature of reality. Among the numerous experimental demonstrations that have shed light on the peculiar behavior of quantum systems, the delayed-choice quantum erasure stands out as a captivating phenomenon. This phenomenon, first proposed by Wheeler in 1978 [1], explores the counterintuitive nature of quantum mechanics by raising the question of whether an observer's choice, made after a quantum particle has already undergone an interaction, can retroactively determine the particle's behavior.

Delayed-choice quantum-erasure experiments have been conducted to investigate the fundamental aspects of quantum mechanics and the role of quantum measurements in shaping the behavior of particles. These experiments have provided insights into the nature of the wave-particle duality for retro-causality within the quantum realm. The concept of delayed-choice quantum erasure has also been applied to various quantum technologies, such as quantum information processing, quantum cryptography, and quantum communication.

In recent years, significant progress has been made in the field of delayed-choice quantum erasure theoretically and experimentally. The utilization of entangled photons, in particular, has enabled precise control and manipulation of quantum states, facilitating the exploration of delayed-choice quantum erasure in increasingly intricate experimental setups.

Several recent studies have further contributed to our understanding of delayed-choice quantum erasure. For instance, Peruzzo *et al.* [2] described a quantum delayed-choice experiment that investigated the wave-particle duality of quantum systems. They demonstrated that a photon could exhibit both particle-like and wave-like behaviors simultaneously. The experiment replaced the delayed choice of the observer in the original thought experiment with nonlocality, and strong nonlocal correlations were observed. This confirmed the genuinely quantum nature of the photon's behavior, highlighting its ability to behave as both particle and wave natures. Kaiser *et al.* [3] focused on the measurement apparatus-dependent nature of the wave-particle complementarity in quantum physics. They performed a delayed-choice experiment in a Mach-Zehnder interferometer using pairs of polarization-entangled photons. By manipulating the behavior of one photon in the interferometer and observing the other, they observed a wave, particle, or intermediate behavior. The experiment also allowed for the continuous morphing of the tested photon's behavior, demonstrating the limitations of a simplistic wave or particle description of light.

Originally, Kim *et al.* [4] firstly conducted the delayed "choice" quantum eraser using entangled photons in a double slit system. They showed that a delayed choice of measurements decided retrospectively the undecided nature of entangled photon characteristics between the particle-like and wave-like natures, where the delayed choice was to determine which-path information of a paired photon even after detection of the other paired photon. This research showed fascinating capabilities of entanglement in manipulating and controlling the behavior of a photon nature.

In this paper, we experimented with delayed-choice quantum erasure using coherent photons. These photons were generated from an attenuated continuous wave (cw) laser and provided orthogonally in an MZI for the post-measurement to see the pre-determined nature of the photons. To achieve this, we employed an MZI consisting of a polarizing beam splitter (PBS) and a beam splitter (BS) to determine the particle nature of the photons. Thus, the which-way information of a single photon inside the MZI is predetermined, leading to the absence of interference fringes in the MZI's output ports.

Despite not directly controlling the MZI itself, we managed the system to experimentally retrieve the wave nature of the photon by manipulating the polarization basis of the output photon using a polarizer. The crucial observation was whether interference fringes appear by the post-measurement. The presence of such fringes indicated a violation of the cause-effect relation, as the polarizer's choice satisfied a space-like separation. To verify single-photon states, we measured both first- and second-order intensity correlations using a coincidence counting unit. This allowed us to explore the intriguing dynamics of delayed-choice quantum erasure and its implications for the relationship between cause and effect in quantum systems.

II. THEORY

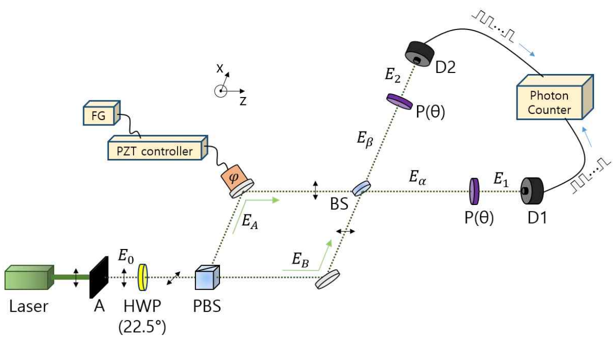

Fig. 1. Schematic of PBS-BS MZI. A: attenuator(ND filters), HWP: half-wave plate, PBS: polarizing beam splitter, BS: non-polarizing beam splitter, P: polarizer, D: single photon detector, FG: function generator, PZT: piezo-electric transducer.

Figure 1 shows the schematic of PBS-BS MZI for the delayed-choice quantum erasure. The laser L is cw light, and the phase controller φ is adjusted by a PZT controller. The coherence length of the laser is 3 mm and the wavelength is 532 nm. In the PBS-BS MZI, a single photon is superposed with orthogonal polarization bases, resulting in no interference fringes as a function of φ. The polarizers (Ps) determine whether a single photon behaves like a wave or a particle. Retrieving interference fringes by the action of Ps indicates a contradiction in causality. We further analyze what causes the quantum eraser and how the wave and particle properties are determined by post-measurements. According to Poisson statistics, the generation ratio of higher-order bunched photons is ~1 % of single photons in a low mean photon number. Most of all, MZI does not discriminate a single photon from cw light.

III. ANALYTICAL SOLUTIONS

The analytical solution for Fig. 1 is represented as [5]:

$$\begin{bmatrix} |E_\alpha\rangle \\ |E_\beta\rangle \end{bmatrix} = \frac{E_0}{\sqrt{2}}[BS][\varphi]\begin{bmatrix} |E_A\rangle \\ |E_B\rangle \end{bmatrix} = \frac{E_0}{\sqrt{2}}\begin{bmatrix} i\left(|\leftrightarrow\rangle + |\updownarrow\rangle e^{i\varphi}\right) \\ |\leftrightarrow\rangle - |\updownarrow\rangle e^{i\varphi} \end{bmatrix}, \quad (1)$$

where $[BS] = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & i \\ i & 1 \end{bmatrix}$ and $[\varphi] = \begin{bmatrix} 1 & 0 \\ 0 & e^{i\varphi} \end{bmatrix}$. E_0 is the amplitude of a single photon. The symbol $\leftrightarrow$ ($\updownarrow$) represents a unit vector of the horizontally (vertical) polarized photon. In the MZI, $|E_A\rangle = i\frac{E_0}{\sqrt{2}}|\updownarrow\rangle$ and $|E_B\rangle = \frac{E_0}{\sqrt{2}}|\leftrightarrow\rangle$ are provided in the upper and lower paths, respectively by PBS, resulting in distinguishable photon characteristics on BS. The purpose of the half-wave plate (HWP) rotated at 22.5° is for the same probability amplitude of photon distribution in MZI. Thus, the mean intensities of E_α and E_β in Eq.(1) are $\langle I_1\rangle = \langle I_2\rangle = \langle I_0\rangle/2$, where $I_i = E_i E_i^*$. These results are from the coherence effect of PBS-BS MZI for perfect "which-way" information.

After the polarizer rotated at an angle θ, the photons are described as:

$$\boldsymbol{E_1} = \frac{iE_0}{2}(\sin\theta + \cos\theta\, e^{i\varphi})\hat{p}, \quad (2)$$

$$\boldsymbol{E_2} = \frac{E_0}{2}(\sin\theta - \cos\theta\, e^{i\varphi})\hat{p}, \quad (3)$$

where θ denotes the angle of rotation for P. Hence, Eqs. (2) and (3) indicate the polarization projections of the outgoing photon onto the polarizers: $|\hat{\updownarrow}\rangle \rightarrow \cos\theta\,|\hat{p}\rangle$ and $|\hat{\leftrightarrow}\rangle \rightarrow \sin\theta\,|\hat{p}\rangle$. The positive θ is for the clockwise direction from the vertical axis. The act of projecting onto the polarizer P symbolizes the implementation of the delayed-choice mechanism, satisfying the space-like separation. For this, the upper and lower path lengths of MZI are set to be 2 m, where the resolving time of the single photon detector (photon counter) is sub-ns (6 ns).

The corresponding intensities are as follows:

$$\langle I_1\rangle = \frac{\langle I_0\rangle}{4}\langle 1 + \sin 2\theta\cos\varphi\rangle, \quad (4)$$

$$\langle I_2\rangle = \frac{\langle I_0\rangle}{4}\langle 1 - \sin 2\theta\cos\varphi\rangle. \quad (5)$$

Equations (4) and (5) are the analytical solutions of the quantum eraser depicted in Fig. 1. In this setup, each individual photon satisfies coherence optics, leading to self-interference in the MZI [6]. The low mean photon number set for Fig. 1 ensures that no coherence between consecutive photons exists, resulting in a statistical ensemble [6]. For $\theta = 0$, photons are in states of distinguishability, resulting in no quantum eraser. For $\theta = 45°$, however, interference fringes are recovered. Thus, the predetermined particle nature of photons in Fig. 1 is erased, and the wave nature of indistinguishability is retrieved with perfect visibility:

$$\langle I_1\rangle = \frac{\langle I_0\rangle}{4}\langle 1 \pm \cos\varphi\rangle, \quad (6)$$

$$\langle I_2\rangle = \frac{\langle I_0\rangle}{4}\langle 1 \mp \cos\varphi\rangle, \quad (7)$$

IV. EXPERIMENTAL RESULTS

Figure 2 shows the experimental results of the measured photons by D1 and D2 in a coincidence detection scheme. The x-axis indicates the phase of φ controlled by PZT for the path length difference between the upper and lower paths of the PBS-BS MZI. The PZT scan speed is adjusted to see the interference fringe patterns via the single photon counting module. The y-axis indicates measured photon counts per 0.1 second by the single photon counting module.

For the experimental data in Fig .2, firstly, the path-length difference is set to be nearly zero. Secondly, the polarizer's rotation angle is controlled for $\theta = 0°$, $\theta = 45°$, $\theta = 90°$, and $\theta = 135°$. At each θ, PZT is scanned for 2π ≤

$\varphi \leq 2\pi$. Thirdly, the measured results are plotted in Figs. 2(a)~(c).

In Fig. 2(a), the black (I_1) and red (I_2) curves show fringes, demonstrating the quantum eraser of the Eqs. (6) and (7) for $\theta \in \{45°, 135°\}$. The data individually measured by single photon detectors (SPCM-AQRH-14) are sent to a FPGA-based single photon counter (DE2). On the contrary, in the Fig. 2(b), I_1 and I_2 show no fringes for $\theta \in \{0°, 90°\}$, resulting in no quantum eraser, as shown in the Eqs. (4) and (5). Figure 2(c) shows the coincidence detection C_{12} (counts/1s). The black and red curves with fringes are for $\theta \in \{45°, 135°\}$, which is the same as the intensity product of the Eqs. (6) and (7) in the Fig. 2(a). These coincidence counts are not for quantum but classical, i.e., intensity product between $\langle I_1 \rangle$ and $\langle I_2 \rangle$. The coincident photon counts meet the Poisson statistics.

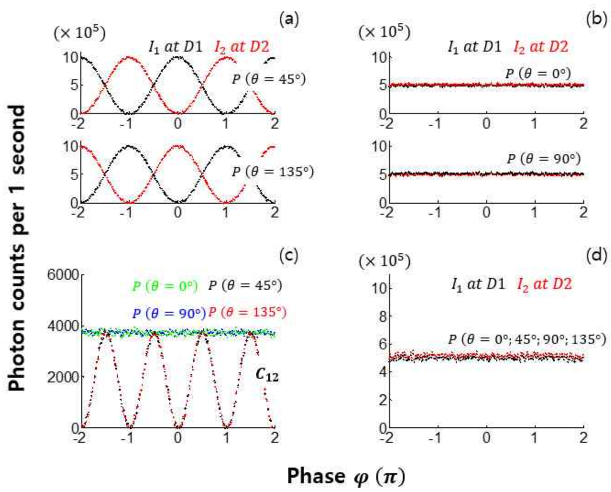

Fig. 2. Experimental results of the delayed-choice quantum eraser. Single photon counts for (a) $\theta \in \{45°, 135°\}$ and (b) $\theta \in \{0°, 90°\}$. (c) Coincidence counts for (a) and (b). (d) Photon counts for an incoherent condition for $\theta \in \{0°, 45°, 90°, 135°\}$. Black (red) curve is for D1 (D2).

In Fig. 2(d), we set the path-length difference to be much longer than the coherence length for an incoherence condition. Regardless of the polarizer's angle, no fringe is observed. This means that the crucial requirement of the quantum eraser is the coherence of a single photon in the MZI. So far, this aspect has not been given much serious attention in spite of its apparent significance. The observed fringes in Fig. 2 reconcile the enigmatic nature of the quantum eraser, whose intensity correlations are for the first order. The origin of the observed quantum eraser is in the reduced measurement events provided by the quantum system. The no fringe without Ps, as shown in Figs. 2(b), is simply due to polarization-basis randomness superposed by BS, whose physics is different from Fig. 2(d). The polarization projection of the measured photons through a polarizer is simply is filtering process for a common basis, resulting in selective choice-based fringes. For this, the coherence condition of each photon is necessary, as demonstrated in Fig. 2(d). Thus, the delayed-choice quantum eraser is nothing but due to measurement-event modification under coherence optics. According to the self-interference of a single photon, even cw light does show the same results as single photons do in Fig. 2 (not shown).

V. Conclusion

The delayed-choice quantum eraser was experimentally demonstrated using predetermined coherent photons via polarization-basis manipulations in a coincidence detection scheme. The polarization-basis manipulation was conducted by a polarizer. Depending on the rotation angle of the polarizer, the interference fringe was retrieved, demonstrating the violation of the cause-effect relation in conventional quantum eraser experiments. From the experimental setup, corresponding coherence solutions were derived analytically for the quantum eraser. Similar to traditional delayed-choice quantum erasers that utilize orthogonal polarization bases, the intrinsic particle-like (distinguishable) photon characteristics were erased in a delayed choice, and the wave-like nature (indistinguishable) of a photon was retroactively recovered in a space-like regime. We further discussed that the origin of the quantum eraser is rooted in the selective choice of measurement events at 50 %. Thus, the mysterious quantum phenomenon with violation of the cause-effect relation was reconciled under coherence optics via modification of measurement events.

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