A macroscopic version of the delayed-choice experiments using coherent photons via post-measurements of polarization bases

Sangbae Kim and Byoung S. Ham
School of Electrical Engineering and Computer Science, Gwangju Institute of Science and Technology
123 Chumcangwagi-ro, Buk-gu, Gwangju 61005, S. Korea
(Submitted on Feb. 15, 2022, bham@gist.ac.kr)

Abstract:
Quantum superposition is the cornerstone of quantum mechanics, where interference fringes originate in the self-interference of a single photon via random probability amplitudes of finding the photon in both paths. Wheeler’s delayed-choice thought experiments have been extensively demonstrated over the last decades to understand the complementarity between the wave-like and particle-like behaviors of a single particle. Here, we propose and demonstrate a macroscopic version of the delayed-choice experiments using coherent photons, where the delayed choice is conducted via post-projection of polarization bases onto a rotated polarizer. Unlike most delayed-choice schemes limited to the complementarity of a quantum particle in an interferometric system, the present scheme is for post-control of output photons in polarization bases, where photon numbers are irrelevant to the observed violations of causality. Thus, the present demonstrations should expand the scope of the quantum mystery into a macroscopic realm.

Introduction
The quantum superposition-caused delayed-choice experiments proposed by Wheeler in 1978 [1], which is based on Heisenberg’s uncertainty principle and Bohr’s complementarity theory [2], have been intensively studied over the last several decades [3-17]. The delayed-choice experiments in a Mach-Zehnder interferometer (MZI) represent an intrinsic quantum feature of superposition between the particle and wave natures of a photon or particle [3]. Such quantum mystery has been conducted using thermal lights [4], entangled photons [5-9], atoms [10-12], or neutrons [3]. In the Wheeler’s delayed-choice experiments, a post-control of the polarization of an MZI results in a paradoxical phenomenon between the wave and particle natures [13]. A quantum version of the delayed-choice experiments has also been presented using a quantum logic gate [14,15]. The delayed-choice experiments have shown an intrinsic quantum property of complementarity between the particle and wave natures of a single particle, where the two natures cannot appear simultaneously or be predetermined.

In the present paper, a macroscopic version of the delayed-choice experiments is presented using coherent photons in an MZI via post-measurements of polarization projections onto a rotated polarizer. Unlike conventional delayed-choice schemes limited to a single particle via measurement control of MZI itself, the present scheme is for post-measurements of the MZI output photons, where the contradictory phenomenon of the cause-effect relation is tested by an inserted polarizer for polarization projection. Here, the MZI (PB-MZI) is composed of a polarizing beam splitter (PBS) and a beam splitter (BS), satisfying the criteria of a noninterfering interferometer according to the Fresnel-Arago law [16]. Thus, the PB-MZI output photons are predetermined to have no interference fringe, where the performed delayed-choice experiments for polarization projection of MZI output photons onto a polarizer are for the violation of causality of this predetermined nature. A similar quantum version of the delayed-choice experiments has been demonstrated using superposed entangled-photon pairs in a double-pass spontaneous parametric down conversion (SPDC) scheme [17]. Due to the coherence feature of MZI outputs, however, the present demonstration can be applied to both single (quantum) and ensemble photons (classical). Thus, the present model is a macroscopic (classical) version of the Wheeler’s delayed-choice experiments, and addresses a fundamental question on quantum mechanics.

Results
A macroscopic version of the delayed-choice experiments
**Fig. 1** A macroscopic version of the delayed-choice experiments. (Dotted circle) Projection onto a polarizer. L: laser, HWP: half-wave plate, PBS: polarizing beam splitter, H (V): horizontal (vertical) polarization, M: mirror, PZT: piezo-electric transducer, BS: beam splitter, P: polarizer, D: single photon detector. The light of laser L is vertically polarized with respect to the plane of incidence. Each colored dot indicates a single photon having the same probability amplitude.

Figure 1 shows schematic of the coherent photon-based macroscopic version of the delayed-choice experiments, where the noninterfering PB-MZI is composed of orthonormal bases of vertical (V) and horizontal polarizations of a photon. For this, a PBS and a BS are combined together for the deterministic particle-like nature of a photon. The PB-MZI output photons are conducted for the post-measurements of their polarization bases through a pair of polarizers Ps. The input field $E_0$ denotes an amplitude of a single photon achieved from an attenuated laser L, where its mean photon number is set to be extremely low, satisfying the incoherence condition between consecutive photons. In other words, the post-measurements are for a statistical ensemble of independent entities. For this, the laser L is chosen to be ultrawide (~THz) in its spectral width, such that the mean distance between consecutive photons is to be far greater than the coherence length $l_c$ (~3 mm) of the laser L. Here, an attenuated single photon’s coherence time has already been tested to be the same as ensemble photons of the laser [18]. In the present experiments, the mean photon generation rate is kept to be ~1 Mbps, satisfying the incoherence condition of the PB-MZI between consecutive photons.

For the delayed-choice experiments in Fig. 1, the most important conditions of the PB-MZI is both orthonormal polarization bases and coherence between two bases. The orthonormal bases condition is accomplished by a half-wave plate (HWP), while the coherence condition is satisfied by adjusting the PB-MZI path-length difference ($\Delta L$) far less than the coherence length $l_c$ (see Fig. 2). The statistical nature of attenuated photons is governed by classical physics of Poisson distribution, where multiply bunched photon rates exponentially drop as the photon number increases according to Poisson statistics. In Fig. 1, the role of the half-wave plate (HWP) placed right after the laser L is to generate polarization randomness of each input photon for the PB-MZI, where the polarization axis of the HWP is actually rotated by 22.5 degrees with respect to the vertical polarization axis. As a result, the PB-MZI gives an equal chance of polarization-determined path choices to a single photon between the upper path (UP) and lower path (LP). Thus, each output photon ($E_1$ or $E_2$) from the PB-MZI is denoted as a superposition state of the orthonormal polarization bases at equal probability amplitudes. This polarization-basis randomness of the PB-MZI results in local randomness in each output port measurements, which is an essential condition for nonlocal correlation in Bell measurements [19].

Unlike the original Franson scheme [20], the incoherence feature of the PB-MZI is accomplished by randomness of orthogonal polarizations. At the same time, the PB-MZI is maintained to be coherent to each single photon for the path-choice probability amplitudes, where the path-length difference $\Delta L$ between UP and LP is kept to be far less than $l_c$. Regarding the wave-particle duality of a single photon, the PB-MZI is predetermined for the particle property, resulting in no interference fringe. Thus, we now focus on the post measurements of the MZI output photons via polarization projections onto a polarizer P inserted after the MZI (see Inset of Fig. 1). This scheme is quite similar to ref. 17, where double-pass type I SPDC process generates vertically polarized photon
pairs in both directions with the same probability amplitudes. According to causality, this type of post-measurements cannot affect the predetermined PB-MZI with respect to the phase $\varphi$, satisfying local realism. Thus, any violation of the local realism witnesses the violation of causality, resulting in a mysterious quantum feature. In terms of coherence feature of the PB-MZI, the delayed-choice measurements should be no difference between a single and an ensemble of photons as an input. This is the physical background of the present macroscopic (or classical) version of the delayed-choice experiments.

Analysis

According to the coherence optics in the PB-MZI in Fig. 1 for a single photon $E_0$, the following matrix representation is obtained for the output photons:

$$
\begin{bmatrix}
E_1 \\
E_2
\end{bmatrix} = \frac{E_0}{2} \left( [BS][\Phi][PBS][\text{HWP}] \right) \begin{bmatrix} 1 \\ 0 \end{bmatrix}
$$

$$
= \frac{E_0}{2} \left[ i(\hat{H} + V e^{i\varphi}) \right],
$$

(1)

where $[BS] = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & i \\ i & 1 \end{bmatrix}$, $[\Phi] = \begin{bmatrix} 1 & 0 \\ 0 & e^{i\varphi} \end{bmatrix}$, and $[PBS][\text{HWP}] = \begin{bmatrix} \hat{H} \\ \hat{V} \end{bmatrix}$ Here, $V$ (H) represents a vertically (horizontally) polarized photon. By the followed polarizer (P) inserted after the PB-MZI, each output in equation (1) is transformed into (see Inset of Fig. 1):

$$
E_A = \frac{iE_0}{2} (\sin \theta + \cos \theta e^{i\varphi}),
$$

(2)

$$
E_B = \frac{E_0}{2} (\sin \theta - \cos \theta e^{i\varphi}).
$$

(3)

Equations (2) and (3) represent polarization projections onto the P rotated by an angle $\theta$, resulting in $V \rightarrow \cos \theta$ and $H \rightarrow \sin \theta$. Here, the positive $\theta$ is for the counterclockwise direction from the horizontal axis ($y$) of the photon propagation direction ($z$). For the negative rotation, however, the projections are denoted by $V \rightarrow \cos \theta$ and $H \rightarrow -\sin \theta$. The projection results onto P represent the post-measurements of PB-MZI for the delayed choice experiments, resulting in an unexpected and irrational violation of causality, resulting in the $\varphi$-dependent interference fringe. Obviously, the fringe represents the wave nature of a photon and thus violates the cause-effect relation in the predetermined PB-MZI.

The resulting intensities of equations (2) and (3) are as follows:

$$
I_A = \frac{l_0}{4} (1 + \sin 2\theta \cos \varphi),
$$

(4)

$$
I_B = \frac{l_0}{4} (1 - \sin 2\theta \cos \varphi).
$$

(5)

For $\theta = \pm \frac{\pi}{4}$ (±45°), equations (4) and (5) are rewritten as:

$$
I_A = \frac{l_0}{4} (1 \pm \cos \varphi),
$$

(6)

$$
I_B = \frac{l_0}{4} (1 \mp \cos \varphi).
$$

(7)

For equations (6) and (7), the local randomness of projected photons can also be satisfied by combining both $\theta$ bases, where $\theta \in [-45°, +45°]$. These specific rotation angles of the P are the random polarization bases of PB-MZI. The sum of the polarization bases in equations (6) and (7) corresponds to the entangled photon-pair case of the second-order (χ(2)) nonlinear optical process [17,21]. Nonlocal correlation between equations (6) and (7) always shows a fringe regardless of local realism (see the bottom row of Fig. 2). Regarding the causality violation, equations (6) and (7) witness the quantum feature of the delayed-choice experiments in a coherence scheme and compared to ref. 17 (discussed in Discussion).

Figure 2 shows experimental results of Fig. 1 for both single photons (left column) and continuous wave (cw) (right column). The top and middle rows are for the coherence condition of MZI with $\Delta L \ll l_c$, while the bottom row is for the incoherence condition with $\Delta L \ll l_c$. The colored curves are for different rotation angle $\theta$s of the Ps, where diagonal ($\theta = 45°$) and off-diagonal ($\theta = -45°$) axes result in opposite interference fringes with a near perfect visibility (see the red and blue curves). On the contrary, both zero and $\pi$ rotation result in no fringe as shown in the green and black lines. These observations in Fig. 2 are the same as ref. 17 for an entangled photon case based
on a double-pass SPDC scheme (see Fig. 3c). Thus, the observed fringe in the left column of Fig. 2 for a single photon demonstrates the violation of causality, satisfying the delayed-choice experiments. The right column shows corresponding features of the left column with a cw light, resulting in a macroscopic version of the delayed-choice experiments. These are the unique and unprecedented quantum features of the delayed-choice experiments in a coherence scheme. If the path-length difference of PB-MZI is beyond the coherence length of the laser $L$ ($\Delta L \gg l_c$), equations (6) and (7) are not satisfied as observed in the bottom row of Fig. 2. From these, coherence between probability amplitudes of UP and LP is an essential condition of the quantum feature of the delayed-choice experiments, where entangled photon pairs in ref. 17 are intrinsically satisfied [22].

![Fig. 2 Experimental demonstrations for Fig. 1. (left column) Single photon input. (right column) A cw light input. Red: $\theta = 45^\circ$, Blue: $\theta = -45^\circ$, Green: $\theta = 0^\circ$, Black: $\theta = 180^\circ$. (Top and middle rows) $\Delta L \ll l_c$, where $\Delta L$ is path-length difference between UP and LP. $l_c$ is coherence length of the laser $L$. (Bottom row) $\Delta L \gg l_c$. Photon counts are for 0.1 s. The error rate ($\sigma/\mu$) of each data point for the left column is less than 1 % (see Section A of the Supplementary Information).](image)

**Discussion**

It is the well-known fact that the most mysterious phenomenon in quantum mechanics is quantum superposition as Feynman mentioned earlier [23]. Figure 3a shows a corresponding scheme to Fig. 1, where the outputs of PB-MZI in Fig. 1 are superposition of orthogonal polarization bases with the same probability amplitudes. Figure 3b is another view of Fig. 3a in an interferometric version with a minor difference in phase. In Fig. 3a, one of the split photons (or fields) in terms of the probability amplitudes is rotated by 90 degrees to satisfy the orthogonal polarization bases as in Fig. 1. Then, measurements of both photons are conducted via polarization projection onto a rotated polarizer $P$. The causality violation is tested whether the $\phi$-dependent interference fringe exists as shown in Fig. 4a. The difference between the original Wheeler’s delayed-choice experiments is the location of $P$ as mentioned in Fig 1, where this scheme is similar to that of ref. 17.
Figure 3c shows a quantum version of the Wheeler’s delayed-choice experiments using double-pass SPDC entangled photons, where the entangled photon pairs are probabilistically superposed by the consecutive action of the forward and backward pump photons [17]. Like Fig. 3a, the initially generated entangled photon pairs in Fig. 3c are vertically polarized. By an inserted quarter wave plate (QWP) in one path, however, polarization superposition is satisfied for the detector D1. Due to the 90-degree phase shift between entangled photons [22,24], there is no fundamental difference between Figs. 3a and 3c in terms of polarization superposition to D1. The random probability of the signal and idler photons in SPDC process does not affect the measurement result in D1. Thus, the function of HWP in Fig. 3a and QWP in Fig. 3c is the same. Whether the light source is classical (coherent; Poissonian; ensemble) or quantum (entangled; sub-Poissonian; squeezed), the basis superposition in Fig. 3 represents for independent (polarization basis) entities. Unlike classical independence, however, the superposed polarization bases of a single photon in terms of probability amplitudes must be coherent as demonstrated in Fig. 2. This basis randomness equivalent to indistinguishability must implies coherence between the paired entities and thus must be distinguished from classical independence, resulting in local randomness in nonlocal correlation [19,20].

Fig. 3] Schematics of basis superposition corresponding to Fig. 1. a, Classical beating-based. b, MZI-based corresponding to a. c, Entangled photon-based corresponding to a (see ref. 17). QWP: quarter-wave plate.

Figure 4 shows experimental results of Fig. 3a for four different rotation angles of P. The top panels are with a half-wave plate (HWP) for orthogonal polarizations between two paths. By ±45° rotations of P, the same quantum features are obtained as in Fig. 2, resulting in the causality violation of the delayed-choice experiments (see also equations (2) and (3)). The bottom panels are without HWP, i.e. for the same polarization basis, resulting in no causality violation due to the preset wave nature of a photon. Here, the action of P simply reduces the observed photon intensity into a half for θ = ±45°. As understood by the delayed-choice experiments, the photon characteristic is post-determined whether the photon behaves as a wave- or a particle-like nature. This causality violation applies even to the ensemble (cw) case (see Fig. 4b).

Unlike Fig. 4c, Fig. 3c results in no fringe without QWP due to no possible φ-phase control to a particular polarization entity by the definition of entanglement: |ψ⟩ = 1/√2(|s⟩1|l⟩2 + |s⟩2|l⟩1) [17]. This definition of entanglement is the physical origin of local randomness even without the addition of P-basis summation as mentioned in Fig. 2. Thus, the quantum mystery of the delayed-choice experiments originates in the superposition of the orthogonal bases of a physical entity regardless of a single particle or an ensemble, unless self-coherence between probability amplitudes of a photon is broken, as already been intensively studied in Born rule tests [25,26]. In other words, the quantum mystery of the delayed-choice experiments originates in the superposition of orthogonal bases of a particle, where the particle must be coherent with itself in the interferometric system. Therefore, the number of photons does not matter if interferometric self-coherence is satisfied. In that sense, randomness or indistinguishability in quantum mechanics must be differentiated from individuality or independence in classical (statistical) physics.
Conclusion

In an orthogonally polarized PB-MZI scheme composed of a PBS and BS, the quantum feature of the “delayed choice” was demonstrated via post-control of polarizations of a photon using a polarizer for both single and ensemble photons of coherent light. Unlike conventional methods, the present delayed-choice experiment was demonstrated via polarization projection of the output photons onto a polarizer. The observed fringe in each output port of PB-MZI showed the violation of the cause-effect relation with near perfect visibility, resulting in the witness of quantum mystery of the delayed-choice experiments. The modified post-selection in a beating scheme corresponding to the original PB-MZI also resulted in the same quantum features and compared it with the Wheeler’s delayed-choice experiments based on double-pass SPDC-generated entangled photon pairs in ref. 17. Astonishingly, there was no difference between them. Moreover, cw light also showed the same feature as the single photon case. From this, we can conclude that the origin of the “delayed-choice” is in the superposition of orthonormal bases of a single photon under the condition of self-coherence in an interferometric system. Thus, the number of photons does not matter for this quantum features, resulting in a macroscopic version. The observations of quantum feature in PB-MZI for the delayed-choice experiments open the door to a new challenge of quantum mechanics limited to a microscopic realm so far.

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Methods

In Fig. 1, the laser L is SDL-532-500T (Shanghai Dream Laser), whose center wavelength and coherence length are 532 nm and 3 mm, respectively. For the random but orthogonal polarizations of a single photon, a half-wave plate (HWP) is rotated by 22.5 degrees from its fast axis. The laser L is vertically polarized with respect to the plane of incidence. For single photons, the laser L is attenuated by neutral density filters. For Figs. 2 and 4, the mean photon
number is set at \( \langle n \rangle = 0.04 \). On behalf of the polarizing beam splitter (PBS), perpendicularly and horizontally polarized components of an incident photon are separated into the upper and lower paths, respectively. Both split components of a single photon are recombined in the beam splitter BS, resulting in PB-MZI. Thus, the photons in the PB-MZI in Fig. 1 acts as particles, resulting in no interference fringes in the output ports. The length of each path of the PB-MZI is set at 2 m, and the path-length difference is kept to be far less than 3 mm for the coherence condition. The \( \phi \) phase control of the PB-MZI is conducted by a piezo-electric optic mount (PZT; KC1-PZ, Thorlabs) connected by a PZT controller (MDT693A, Thorlabs) and a function generator (AFG3021, Tektronix). For Figs. 2 and 4, the data is measured under the \( \phi \) scanning mode, where the phase resolution is \( \frac{2\pi}{180} \) radians, i.e., 180 data points for a 2\( \pi \) cycle (see Section A of the Supplementary Information). The BS position for recombination of two split components of a photon is well adjusted for a complete overlap between them.

The measurements for both output photons from PB-MZI in Figs. 2 and 4 are conducted by a set of single photon detectors D1 and D2 (SPCM-AQRH-15, Excelitas) via a coincidence counting module (DE2, Altera). The dead time and dark count rate of the single photon detectors is 22 ns and 50 counts/s, respectively. The resolving time of the single photon detector is ~350 ps, whose generated electrical pulse duration is ~6 ns. For the continuous wave (cw) version in Figs. 2 and 4, the single photon detectors are replaced by silicon photodetectors (APD-110A, Thorlabs). For this, the laser L is approximately attenuated at ~20 \( \mu \)W. The detected cw output signals are sent to a digital oscilloscope (DL9040L, YOKOGAWA) and recorded in a real-time basis. For the polarizers Ps in Figs. 1 and 3, four different rotation angles are used (-45, 0, 45 or 90 degrees) to the counter-clockwise direction with respect to the horizontal axis of the light propagation direction. The photon counts in Figs. 2 and 4 are measured by a home-made Labview program for 0.1 s.

In Fig. 3a, the longitudinal distance of each beam path is 2 m. The minimum transverse distance between two beams (UP, LP) at the position of mirrors is limited to the diffraction limit of ~200 \( \mu \)m by using a D-shaped mirror, resulting in a well-separated spatial interference fringe on the detector position. For Fig. 4, only a center fringe is filtered out through a home-made slit to the detector. For details, see Section B of the Supplementary Information.

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Author contributions S.K conceived the idea, conducted experiments and provided the data. B.S.H. developed the idea, analyzed the data, and wrote the manuscript.

Correspondence and request of materials should be addressed to BSH (email: bham@gist.ac.kr).

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Supplementary information is available in the online version of the paper.