

RESEARCH ARTICLE

The Controlled Phase Shifts of Photons in the Double-Slit Experiment with the Delayed-Choice Quantum Eraser

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Abstract

The delayed-choice quantum eraser (1999 arXiv/2000 PRL) became a signature of modern quantum optics because it shifted attention from a single-screen pattern to the structure of conditional statistics. Its central lesson is operational: interference can be absent in unconditional (singles) counts while reappearing in coincidence-conditioned sub-ensembles, often as complementary fringe and anti-fringe patterns whose sum removes modulation. This architecture transformed complementarity from a slogan into an experimental discipline: reporting marginals and conditionals, making information flow explicit, and designing measurements that separate local statistics from correlation-based structure. This presented new model is based on the oscillating electrical fields E of signal and idler photons – the “white” mode with $E^2 = 1$, the “grey” mode with $E^2 = 0.5$, and the “black” mode with $E^2 = 0$ have been oscillating at the femtosecond time scale. Both the signal and idler photons with their oscillating “color” modes interact with the optical elements on the optical table at the picosecond time scale. The elements on the optical table are arranged in order to measure the delayed-choice quantum eraser within the nanosecond time scale. This proposed “classical” scenario takes into account all sub-ensembles with “white”, “grey”, and “black” clicks at all detectors. It seems that we should experimentally count all of these sub-ensembles and not to delete them from our statistics. The “classical” Nature might surprise us with some unexpected results.

Keywords: Classical Instructions for Photons, Delayed-Choice Quantum Eraser, Interference of Two Sub-Ensembles of Photons, “Riddle-Like” Discussions.

1. Introduction

Few table-top optics experiments from the late twentieth century entered the culture of physics as deeply as the delayed-choice quantum eraser [1],[2]. Its staying power comes from a simple but unsettling arrangement: a signal photon is recorded at a scanning detector, while its entangled idler partner is routed through an interferometric network that either preserves or erases which-path information – and the idler outcome can occur after the signal detection. The experiment’s influence is best measured not by drama of “delayed choice” language, but by the habits

it trained: to separate marginal from conditional distributions, to treat interference as a statement about joint probabilities, and to make the measurement context explicit in both design and reporting [3]-[23].

The very important information from these experiments is the counting statistics [24],[25] in delayed-choice quantum eraser experiments. Table I collects approximate data on the joint detections of the signal and idler photons, individual single detections of the signal and idler photons, and no detections of signal or idler photons after the pump photons entered into the system.

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Table 1. Detections between a “signal” photon and its “idler” partner in a typical delayed-choice quantum eraser experiment.

Detection of the signal photon	Detection of the idler photon	Measurable rates
yes	yes	~ 0.04
yes	no	~ 0.16
no	yes	~ 0.16
no	no	~ 0.64

The traditional interpretation of this coincidence detections is based on the real lossy sources and detectors, most generated photon pairs do not produce a joint detection; instead, one often records far more single detections than coincidences. In many cases there is observed no detection of signal and idler photons at all. Is there a possibility to interpret these sub-ensembles as the result of the phase shifts of both signal and idler photons?

This paper was inspired by the valuable papers of Grangier, Roger and Aspect on single photon interferences [26]-[28] and by papers of Villas-Boas et al. on the bright and dark states of light as the quantum origin of classical interference [29]-[31].

2. “White”, “Grey” and “Black” Photons in the Delayed-Choice Quantum Eraser

Electromagnetic wave is a self-propagating wave of the electromagnetic field with sinusoidally oscillating electric field E . We propose a model where the “white” photons with $E^2 = 1$ cannot penetrate through the silver layer in a beamsplitter and are always reflected. On the other side, the “black” photons with $E^2 = 0$ easily transmit through a beamsplitter. The beamsplitter acts as a filter to separate “white” and “black” photons. The third group of “grey” photons with $E^2 = 0.5$ can be reflected and transmitted through a beamsplitter in the ratio 50:50. This situation is shown schematically by Fig. 1 and Fig. 2.

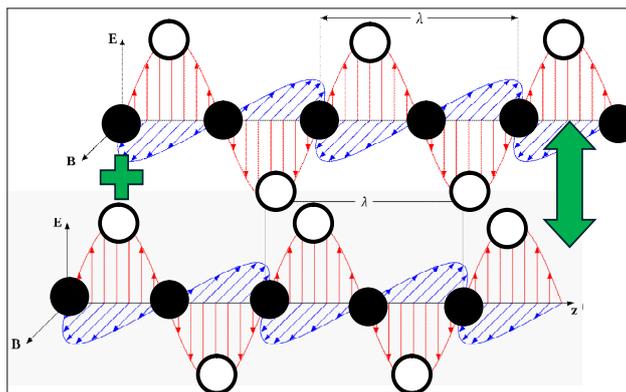


Figure 1. Two complementary electromagnetic waves with their sinusoidal electromagnetic fields.

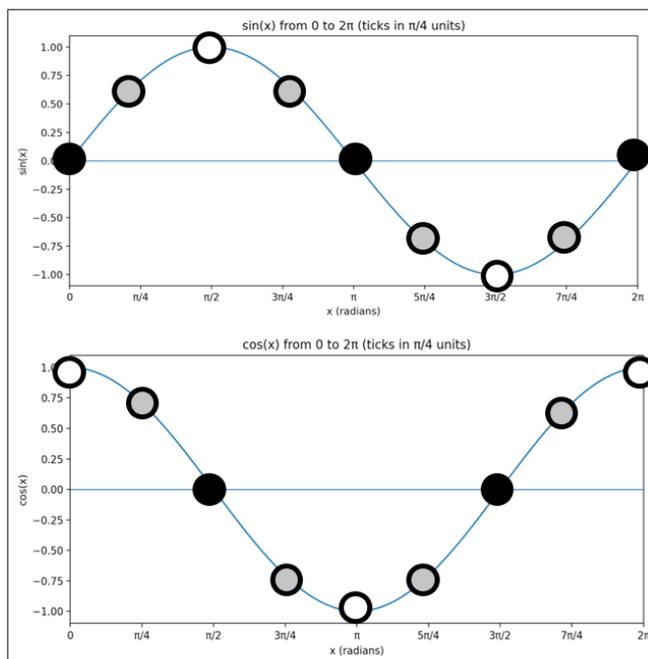


Figure 2. Two complementary electromagnetic waves with their sinusoidal electromagnetic fields: transmutations of white, grey and black photons during the photon journey through the optical table with elements to demonstrate a delayed-choice quantum eraser.

3. Evolution of Photons During their Path Through the Optical Table with the Delayed-Choice Quantum Eraser

At the input to the double-slit experiment the 351.1 nm argon laser beam is divided by a double-slit and incident onto a type-II phase matching nonlinear optical crystal BBO followed by the Glan-Thompson prism. We assume the 50:50 mixture of “white” and “black photons”. A pair of 702.2 nm orthogonally polarized signal and idler photons are generated with a phase shift with a difference $\Delta\Phi = \pi$. The signal photon passes to scanning detector D0. The idler photon is sent to an interferometer with equal-path optical arms. The interferometer includes a prism PS, two 50-50 beamsplitters BS_a and BS_b, two reflecting mirrors M_a and M_b, and a 50-50 beamsplitter BS_c. The beamsplitters act as a filter and moreover converse

the original white photon into black one ($-\pi/2$) and the black photon is converted into the white photon ($+\pi/2$). The total phase shift difference of these two photons is $\Delta\Phi = \pi$. The “beam splitter mystery” of the phase shifting in the beamsplitters of the Mach-Zehnder interferometer was studied in details by Hénault [32]. During the tour of idler photons through this interferometer their phase shifts are several times modified on each contact with beamsplitters and mirrors. At the end we prepare two sub-ensembles of “grey” photons with the phase difference $\Delta\Phi = \pi$ that create interference fringes. The detection of signal photons by the detector D0, and the detection of idler photons by detectors D1, D2, D3, and D4 gives us many important correlations of these formed sub-ensembles of photons. Fig. 3 shows the schema of the Kim et. al interferometer [1].

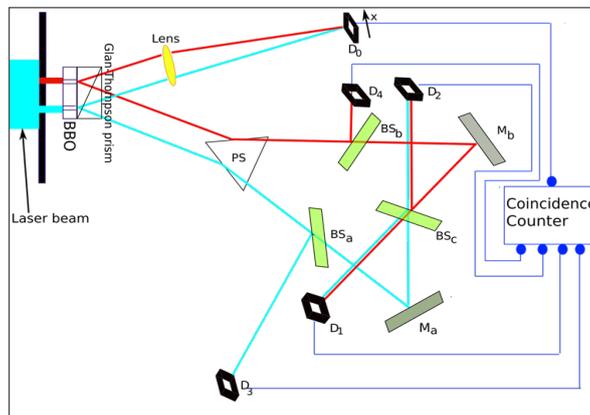


Figure 3. Schema of the optical table used by Kim et al. for the delayed-choice quantum eraser [1] (figure from Wikipedia [33]).

Fig. 4 surveys patterns extracted from these sub-ensembles of photons: R₀₁ from D0 and D1, R₀₂ from D0 and D2, R₀₃ from D0 and D3, R₀₄ from

DO and D4. One important information from those interference patterns follows: $\Delta\Phi(R_{01}-R_{02}) = \pi$.

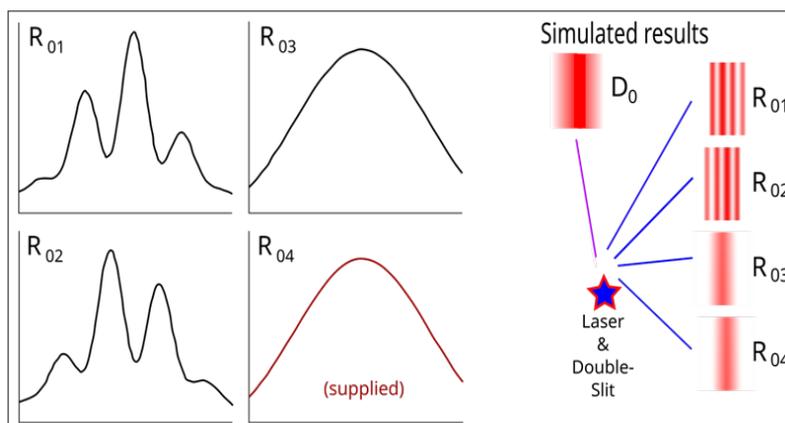


Figure 4. Correlations from sub-ensembles extracted by Kim et al. for the delayed-choice quantum eraser [1] (figure from Wikipedia [33]).

4. Phase Shifts of Signal and Iidler Photons in the Delayed-Choice Quantum Eraser

The set of optical elements on the optical table designed by Kim et al. [1] could prepare several sub-ensembles of signal and idler photons. The pump

photons at the input to this optical table are in the 50:50 “white” and “black” states. In the BBO crystal the pump photons create two orthogonally polarized signal and idler photons with a phase shift difference $\Delta\Phi = \pi = [+3\pi/4 - (-\pi/4)]$. These “grey” signal and idler

photons generate the joint clicks and interference patterns. In more cases the input “white” and “black” photons generate two sub-ensembles of “white” and “black” signal and idler photons with a phase shift difference $\Delta\Phi = \pi = [\pi-0]$. These sub-ensembles of signal and idler photons lead to a single click in the set of detectors D0, D1, D2, D3, and D4. However, the most typical sub-ensemble of signal and idler photons generates no clicks at those detectors. In this case “white” pump photons enter into the system and create two entangled photons with the phase shift difference is $\Delta\Phi = \pi = [\pi/2-(-\pi/2)]$. It seems that this behavior of photons is energetically the most favorable case.

This model takes into account the existence of all sub-ensembles of signal and idler photons. All sub-ensembles play an important role and should not be deleted from the total statistics. Figs. 5 – 11 document the interplay of the “white” and “black” pump photons with the BBO crystal under the formation of signal and idler photons with different phase shifts. Idler photons on their route through the system of beamsplitters and mirrors form sub-ensembles with the phase shift difference $\Delta\Phi = \pi$ leading to the formation of observed interference patterns. The observed events on this optical table can be described “classically”.

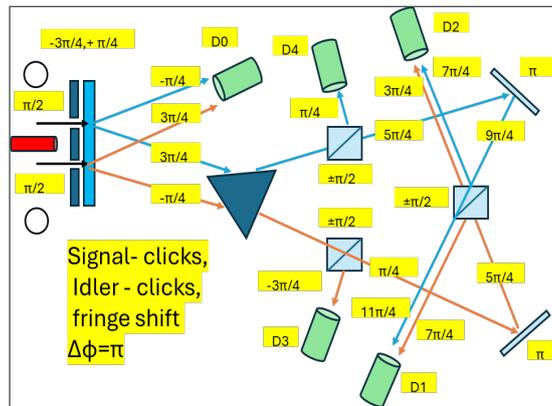


Figure 5. Phase shifts of signal and idler photons in the delayed-choice quantum eraser experiment with the “white” pump photons. The joint clicks of signal and idler photons.

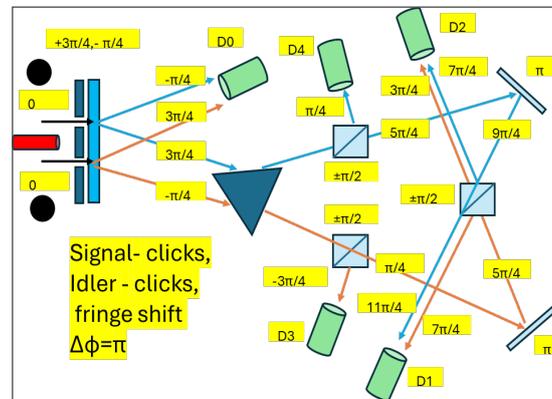


Figure 6. Phase shifts of signal and idler photons in the delayed-choice quantum eraser experiment with the “black” pump photons. The joint clicks of signal and idler photons.

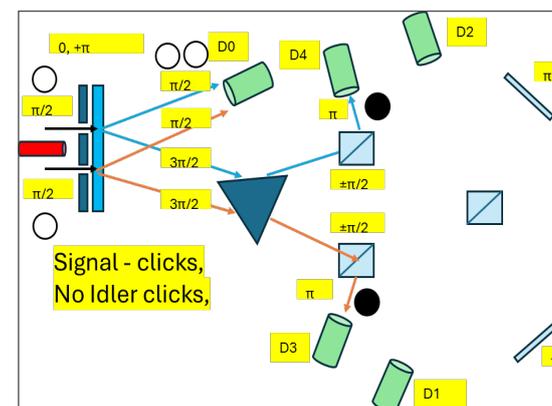


Figure 7. Phase shifts of signal and idler photons in the delayed-choice quantum eraser experiment with the “white” pump photons. The signal photon clicks, no clicks of idler photons.

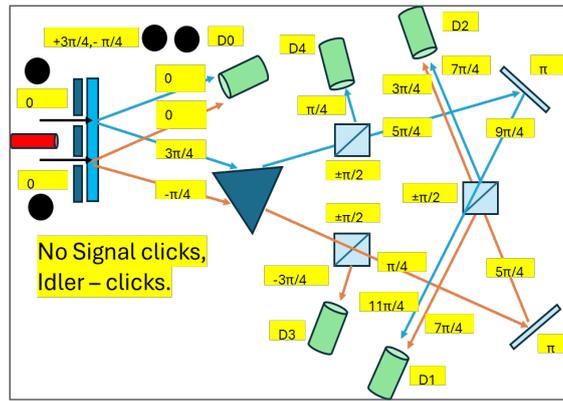


Figure 8. Phase shifts of signal and idler photons in the delayed-choice quantum eraser experiment with the “black” pump photons. No clicks of signal photons, idler photons click.

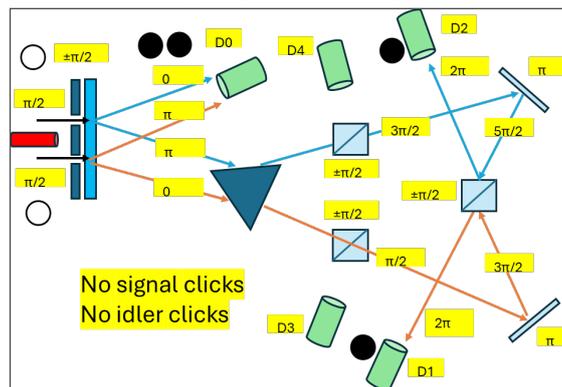


Figure 9. Phase shifts of signal and idler photons in the delayed-choice quantum eraser experiment with the “white” pump photons. No clicks of signal photon, no clicks of idler photons.

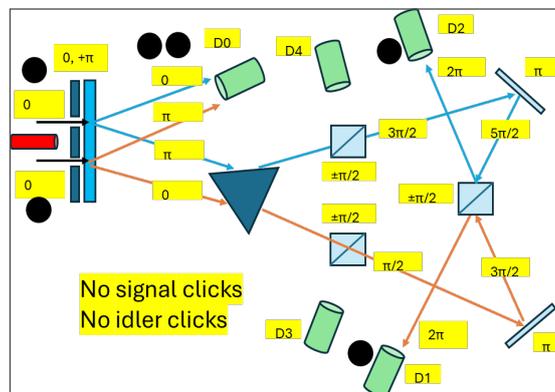


Figure 10. Phase shifts of signal and idler photons in the delayed-choice quantum eraser experiment with the “black” pump photons. No clicks of signal photon, no clicks of idler photons.

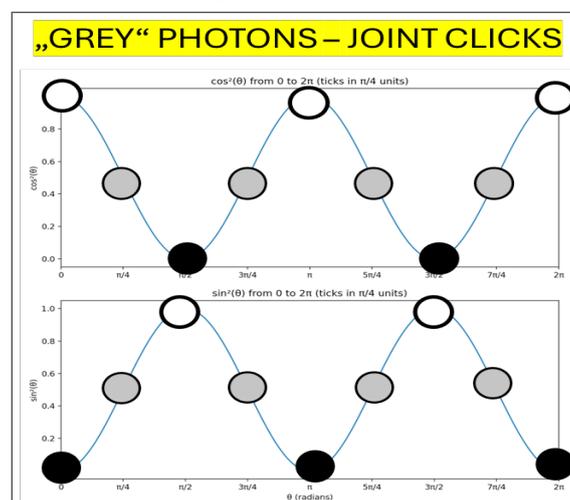


Figure 11. Phase shifts of signal and idler photons in the delayed-choice quantum eraser experiment: “white” $E^2 = 1$, “grey” $E^2 = 0.5$, “black” $E^2 = 0$. Joint clicks for the signal and idler “grey” photons.

5. Conclusion

This model of “white”, “grey” and “black” photons can interpret the “mysterious” properties of photons in the delayed-choice quantum eraser in a “classical” way. The joint “cooperation” of all elements present on the optical table (e.g., source of photons, momentaneous electric field of photons, beamsplitters, mirrors, detectors, etc.) contributes to the final resulting structure in the picosecond time scale [34].

Acknowledgment

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Conflict of Interest

The author declares that there is no conflict of interest.

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