RESEARCH ARTICLE

The Controlled Phase Shifts of Photons in the Mach-Zehnder Interferometer

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Abstract

The Mach-Zehnder interferometer (MZI) is a two-path phase-to-intensity transducer that becomes "mysterious" mainly when one conflates operational facts, minimal predictive calculus, and ontological storytelling. Controlled phase shifts are the central "knob" of the MZI: a tunable relative phase Φ converts directly into complementary output intensities at the two ports. In this model, photons enter the MZI with classical instructions: the "white" photons with $E^2 = 1$ (where E is the electric field of the sinusoidal electromagnetic wave at the given moment) are reflected on the beamsplitters, the "grey" photons with $E^2 = 0.5$ can be both reflected and transmitted through the beamsplitters (with 50:50 ratio), and the "black" photons with $E^2 = 0$ transmit through the beamsplitters. The movable mirrors and the second beamsplitter modify the "color" of photons. The 50:50 mixture of "white" and "black" photons at the input is separated by the first beamsplitter. The phase shifts are modified by movable mirrors so that the second beamsplitter organizes the resulting structure of photons at the two detectors. The interference patterns have been formed from two sub-ensembles of photons with their relative phase shift $\Delta\Phi = \pi$ at the given port. We assume that this classical behavior of photons in the MZI can clarify the "riddle-like" discussions (e.g., delayed choice switching, the meaning of a dark port, and the role of which-way information).

Keywords: Classical instructions for Photons, Interference of two Sub-Ensembles of Photons, Mach-Zehnder Interferometer, "Riddle-like" Discussions.

1. Introduction

The Mach-Zehnder interferometer (MZI) is among the cleanest laboratories for "wave-particle" talk because it can be switched between an open configuration (which-way readout possible) and a closed configuration (paths recombined, interference observed), while keeping the same source, the same arms, and nearly the same optics. Standard treatment show that the output intensities depend sinusoidally on the relative phase between two arms, making the device foundational in precision metrology and quantum optics, e.g. [1] – [10]. Yet, the MZI hosts many "riddle-like" discussions (e.g., delayed choice switching, the meaning of a dark port, and the role of which-way information).

This model was inspired by the valuable papers of Grangier, Roger and Aspect on single photon interferences [11]-[13] and by papers of Villas-Boas et al. on the bright and dark states of light as the quantum origin of classical interference [14]-[16].

A 50/50 beamsplitter is a "two-path" device in the same spirit as the double-slit: it coherently maps one input mode into a superposition of two output modes. The heralded photon is directed onto a nominal 50/50 beamsplitter. Two photodetectors monitor the two output ports. For a true single-photon state, a detection event at one output should preclude a simultaneous detection at the other output (apart from the missed counts and multiphoton contamination). This "particle" aspect can be tested in the open

Mach-Zehnder interferometer. The interferometric test ("wave" aspect) can be evaluated in the closed Mach-Zehnder interferometer. The two outputs of the first beamsplitter are recombined in the second beamsplitter. By scanning a phase delay, several results at the two detectors could be observed. The typical statistics is based on the "bright" counts only. What is the cause of the "missed" counts? Should we include the "missed" counts into the system statistics?

In this paper we argue that much of the riddle dissolves once we apply the "classical" instructions of photons how to behave at the individual components of the MZI during their several nanosecond journey through this device. Are there some "hidden" instructions for each moment of the photon journey through the MZI that could modify their behavior in the picosecond time domain at each interaction with elements on the optical table?

2. "White", "Grey" and "Black" Photons in the Mach-Zehnder Interferometer

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.
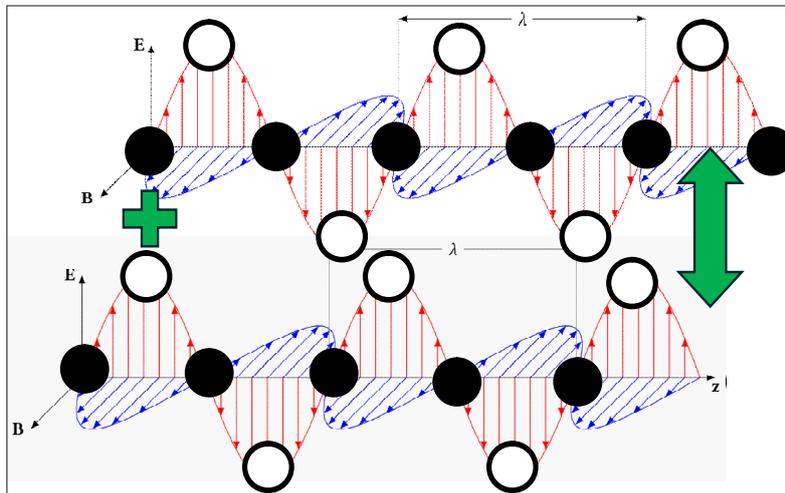

Figure 1. *Two complementary electromagnetic waves with their sinusoidal electromagnetic fields.*
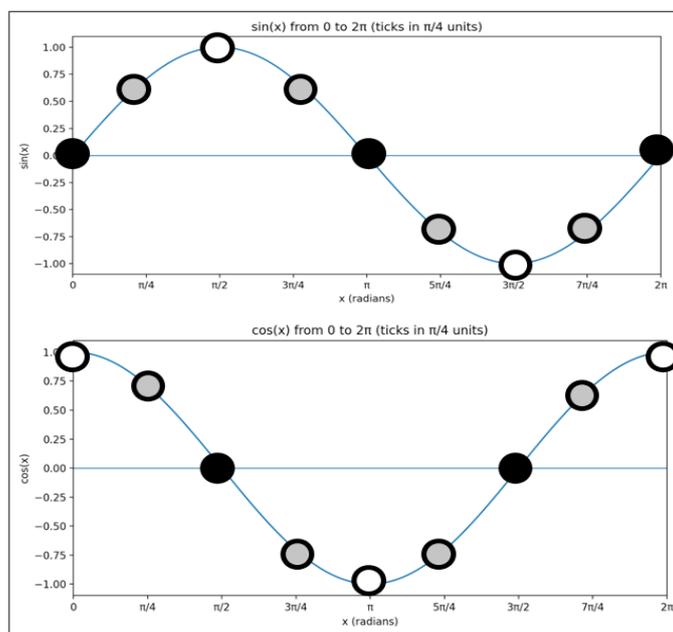

Figure 2. *Two complementary electromagnetic waves with their sinusoidal electromagnetic fields: transmutations of white, grey and black photons at the femtosecond time scale during the photon journey through the Mach-Zehnder interferometer at the nanosecond time scale.*

3. Evolution of Photons During their Path Through the Mach-Zehnder Interferometer

At the input to the Mach-Zehnder interferometer we assume the 50:50 mixture of white and black photons. The first beamsplitter acts 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 MZI was studied in details by Hénault [17]. During the next journey two movable mirrors modify the "color" of photons as it was elegantly experimentally documented by the Grangier group [11]-[13]. At the last step we can work in an open MZI without the second beamsplitter or in a closed MZI with the presence of the second beamsplitter. The second beamsplitter has the same interactions with photons as the first beamsplitter. Moreover, the position of the second beamsplitter might modify the final color of photons - the effect termed as the delayed choice. The formation of observed interference patterns is caused by two sub-ensembles of photons with the phase shift difference $\Delta\Phi = \pi$. Figures 3 – 10 depict numerous effects observed with the open and closed Mach-Zehnder interferometer.
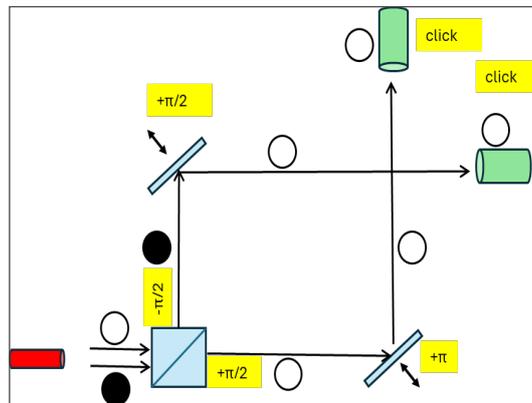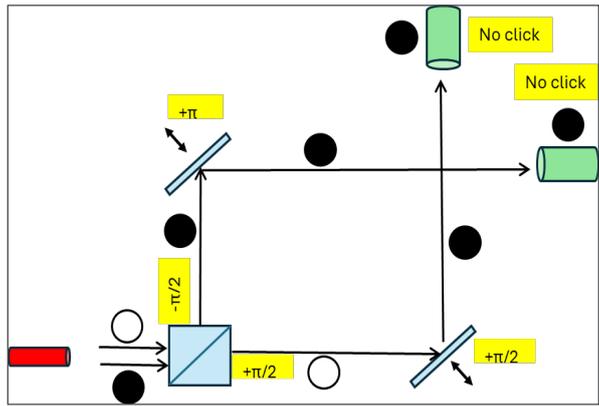

Figure 3. *The journey of individual photons through the open Mach-Zehnder interferometer: movable mirrors are adjusted in order to create white photons detected by both detectors.*
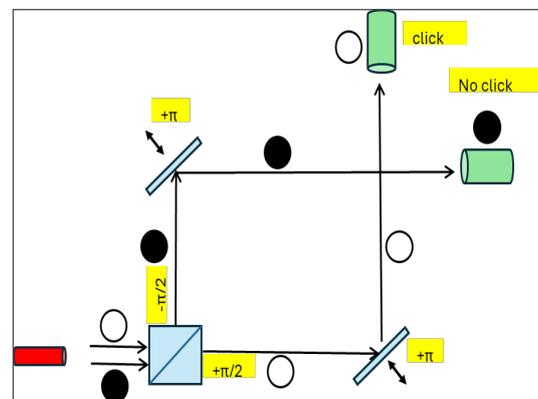
Figure 4. *The journey of individual photons through the open Mach-Zehnder interferometer: movable mirrors are adjusted in order to create white photons detected by one detector.*
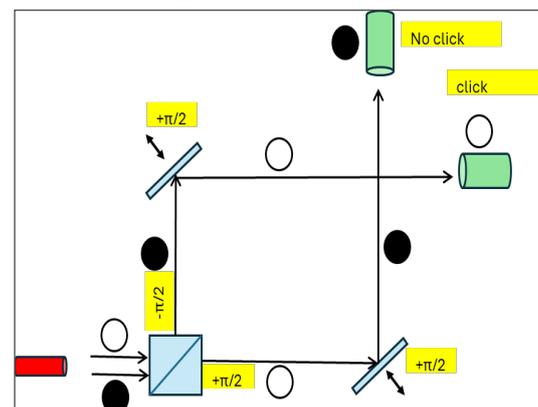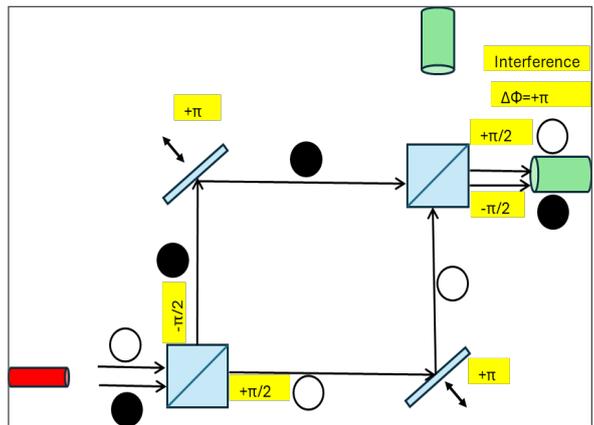

Figure 5. *The journey of individual photons through the open Mach-Zehnder interferometer: movable mirrors are adjusted in order to create white photons detected by one detector.*
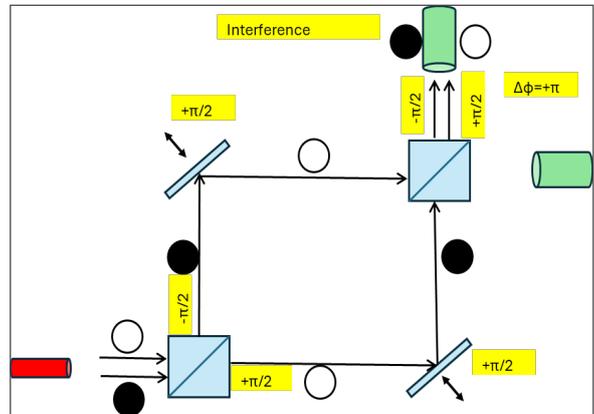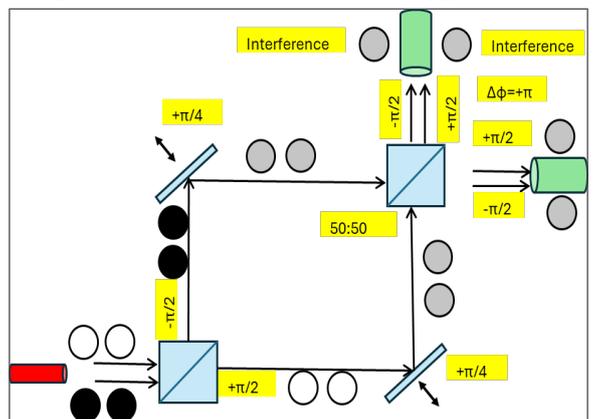
Figure 6. *The journey of individual photons through the open Mach-Zehnder interferometer: movable mirrors are adjusted in order to create black photons without their detection by detectors.*
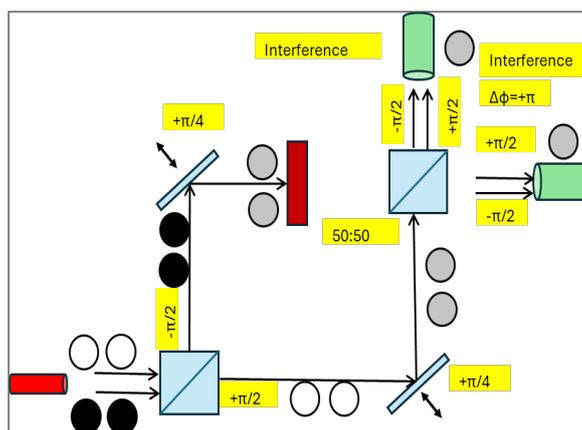
Figure 7. *The journey of individual photons through the closed Mach-Zehnder interferometer: movable mirrors are adjusted in order to create interference patterns from two sub-ensembles of photons with ΔΦ = π at one detector.*

Figure 7. *The journey of individual photons through the closed Mach-Zehnder interferometer: movable mirrors are adjusted in order to create interference patterns from two sub-ensembles of photons with ΔΦ = π at one detector.*
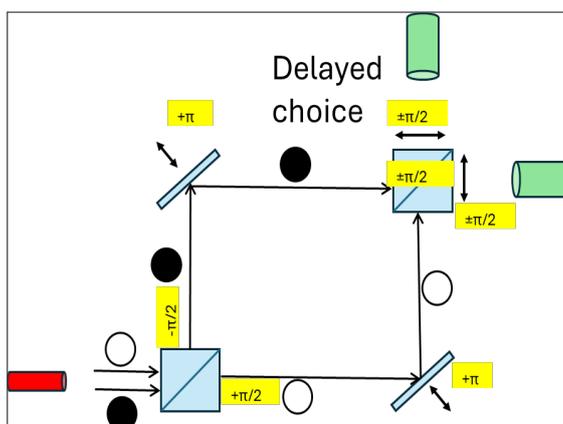
Figure 8. *The journey of individual photons through the closed Mach-Zehnder interferometer: movable mirrors are adjusted in order to create interference patterns from two sub-ensembles of grey photons with ΔΦ = π at two detectors.*

Figure 9. *The journey of individual photons through the closed Mach-Zehnder interferometer with an obstacle in one arm: movable mirrors are adjusted in order to create interference patterns from two sub-ensembles of grey photons with $\Delta\Phi = \pi$ at two detectors.*

Figure 10. *The journey of individual photons through the closed Mach-Zehnder interferometer: the position of the second beamsplitter can dramatically modify the final result at both detectors in the last nanosecond – the delayed choice.*

4. Conclusion

This model of "white", "grey" and "black" photons can interpret the "mysterious" properties of photons in the Mach-Zehnder interferometer 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.

Conflict of Interest

The author declares that there is no conflict of interest.

5. References

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