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Cross-Double-Slit Experiment and Extended-Mach-Zehnder Interferometer

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Abstract

We propose two experimental tools, Cross-Double-Slits and Extended-MZI, for studying quantum phenomena, such as double-slit experiments, "which-way"-double-slit experiment, wave-particle duality, complementarity, causality, Wheeler-delayed-Choice experiment, information send backward in time, interactions between entangled photons. We propose a "Choice-forward" effect/experiment.

Key words: Mach-Zehnder Interferometer, Wheeler-delayed-Choice experiment, entangled photons, wave-particle duality, complementarity, causality, quantum mechanics, double-Slits experiment

Content

1. Introduction

In Young-double-slit experiments, photons form an interference pattern, even emitting one photon at a time. This result is the typical behavior of wave, which is interpreted as that each photon has arrived by both slits at the same time. Feynman stated that this wave-particle dual behavior contains the basic mystery of quantum mechanics.

To test the interpretation, Which-Path-double-slit experiments have been proposed and performed. To determine "which-path" is equivalent to try to find the particle nature of photon in the experiment. The experimental result is that once which slit a photon passing through is determined, the interference pattern disappeared, namely the photon behaviors like a particle. It is interpreted as that two complementary natures, wave and particle, of photons cannot all be observed or measured simultaneously. Bohr called this choice of exhibiting wave- or particle-like behavior "complementarity" and states that the type of measurement performed on a quantum system determines its behavior.

We argue and show later in this article that those two statements may not be equivalent. For this aim we distinguish both statements by different names:

(A) Bohr's statement A: "two complementary natures, wave and particle, of photons cannot all be observed or measured simultaneously".

(B) Bohr's statement B: "the type of measurement performed on a quantum system determines its behavior".

To exclude the interpretation of quantum mechanical complementarity, Wheeler proposed the "delayed-choice" Gedanken-Experiment for exploring whether a photon can "feel" the experimental apparatus in Double-slit experiment and, then adjusts its behavior to fit: "Thus one decides the photon shall have come by one route or by both routes after it has already done its travel". Wheeler's delayed-choice experiment seems to indicate that information can travel backward in time, which challenges the causality.

Moreover, the delayed-choice-quantum-eraser experiment was introduced and performed.

To study wave-particle duality, complementarity, collapse of wave function, causality further, and test their interpretations, in this article, we propose new apparatuses and experiments as below

(1) Cross-double-slit apparatus and experiment, which is an extended Young-double-slit experiment, to push the puzzled situation to more severe situation, i.e., whether a photon passing through four slits at once, instead of two slits;

(2) Which-Way-Cross-Double-Slit Experiment to study whether photons show the two complementary natures, wave and particle, in the same experimental configuration simultaneously; and focus on how to determine whether a photon is either a wave or a particle or both, instead of

pure “which way” measurement;

(3) Extended-Mach-Zehnder Interferometer apparatus and Wheeler-Delayed-Choice Experiments to study complementarity and collapse of wave function further;

(4) Extended-Mach-Zehnder Interferometer Experiments to study whether the present events affect the future events;

(5) Extended-Mach-Zehnder Interferometer Experiments with entangled photons.

2. Cross-Double-Slit Apparatus and Experiment

2.1. Cross-Double-Slit Apparatus

We propose Cross-Double-Slit apparatus (Fig.1), which contains a source capably emitting one photon at a time, a slit wall with four slits, and a screen. Where slits A and B are in z-direction, slits C and D are in y-direction. The photons travel in negative x-direction.

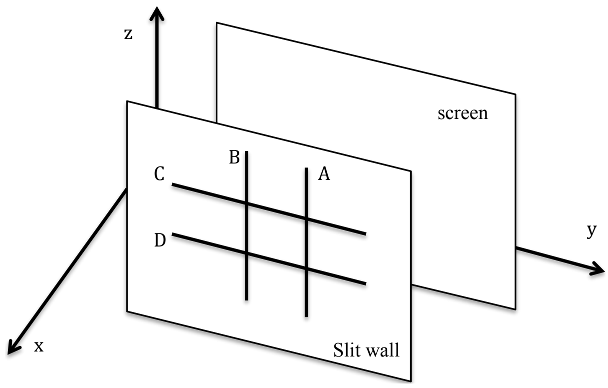


Fig. 1 Cross-Double-Slit Experiment

2.2. Cross-Double-Slit Experiment

Based on the results of regular double-slit experiment, one knew that slits A and B alone cause an interference patter in y-direction on the screen. Similarly, slits C and D alone cause an interference patter in z-direction. The aims of the Cross-Double-Slit Experiment are to determine:

(A) Whether a photon is passing through 4 slits, instead two slits, simultaneously?

(B) Whether slits A and B, and slits C and D cause two set of interference patterns perpendicular to each other?

(C) Whether slits A and C cause some kind of “interference” pattern, as well as slits A and D, slits B and C, and slits B and D?

2.3. Which-Way-Cross-Double-Slit Experiment

Now let’s propose Which-Way-Cross-Double-Slit Experiment by putting an observer near one of slits, say slit A, to observe photons passing through slit A.

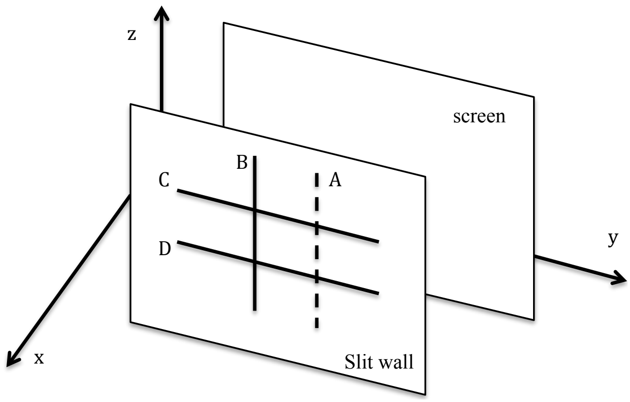


Fig. 2 Which-Way-Cross-Young-Double-Slit Experiment

Since it is known that the "observation" would make the interference pattern disappear, we are not focus on observation of "which way". So in the proposed experiment, one can use an object to block the propagation of photons coming out from slit A (represented by dotted line A in Fig. 2).

What we expect to observe are the following.

(A) Whether the interference pattern due to slits C and D still exists?

(B) If we DO have the interference pattern due to slits C and D, which implies that, a photon acting as wave goes through slits C and D and form interference pattern. However, at the same time, the photons acting as particles pass through slits A and B. In this situation, photons are manifesting both nature of particle (passing through Slits A and B) and wave (passing through Slits C and D) simultaneously, which is a paradox.

(C) If we DO NOT have the interference pattern due to slits C and D, which implies that photons acting as particles go through one of slits B, C and D at a time.

Furthermore, if there are "interference" patterns caused by slits B and C, and by slit B and D, respectively, as mentioned in Cross-Double-Slit Experiment of Section 2.1, we want to find out: Whether, in the Which-Way-Cross-Double-Slit Experiment, the "interference" patterns due to slits B and C, and due to slits B and D still exist? If the answer is YES, then a photon as wave goes through slits B, C and D, although photons also goes through the slit B as particles.

3. Extended-Mach-Zehnder Interferometer and Wheeler-Delayed-Choice Experiment

3.1. Regular Wheeler-Delayed-Choice Experiment

The regular Wheeler-Delayed-Choice Experiment, done on a regular Mach-Zehnder interferometer (denoted as **MZI**) (Fig. 3), aims to decide whether photons sense the experimental apparatus and adjusts its behavior to fit. The key point is that the output beam-splitter (denoted as **BS**) of a MZI is inserted or removed after a photon has entered the interferometer, thus performing a delayed-choice test of the wave-particle complementary behavior.

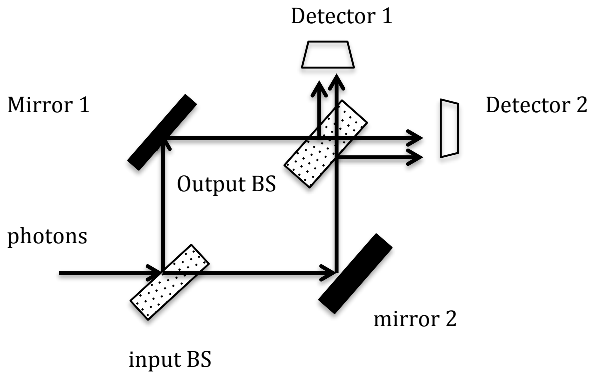


Fig. 3 Regular Mach-Zehnder Interferometer

3.2. Extended-Mach-Zehnder Interferometer

To study how far back in space and time the delayed-choice can affect, explore the particle-wave duality of photons, and explore whether there is a choice-forward behavior (explained later), we propose an Extended-Mach-Zehnder interferometer (denoted as Extended-**MZI**). The Extended-**MZI** contains: a source emitting photons one at a time, the first MZI, the second MZI, and the third MZI, where three MZIs connected in series and collaborated with each other (Fig. 4).

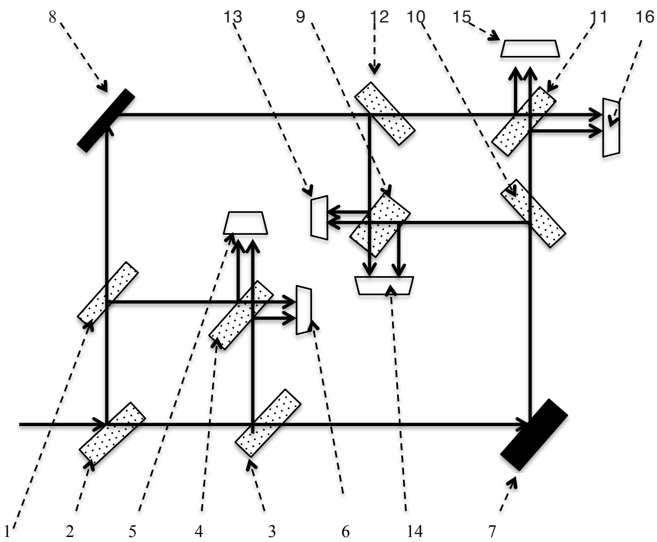


Fig. 4 Extended-MZI

The first MZI contains BS1, BS2, BS3, BS4, and detectors D5 and D6.

The second MZI contains BS1, BS2, BS3, BS9, BS10, BS12, reflect mirrors M7 and M8, and detectors D13 and D14.

The third MZI contains BS1, BS2, BS3, BS10, BS11, BS12, mirrors M7 and M 8, and detectors D15, D16.

The operation of the Extended-MZI is the following.

Photons are introduced into the apparatus, BS2 reflects 50% of total incoming photons toward to M8; 50% total incoming photons pass through BS2 toward to M7. Then:

(1) For the first MZI: BS1 and BS3 reflect 50% of incoming photons toward to D6 and D5, respectively; with BS4 in place, D6 shows an interference pattern.

(2) For the second MZI: BS10 and BS12 reflect 50% of incoming photons toward to D13 and D14, respectively; with BS9 in place, D14 shows an interference pattern.

(3) For the third MZI: 50% of incoming photons pass through BS10 and BS12 toward to D15 and D16, respectively; with BS11 in place, D16 shows an interference pattern.

Thus each MZI performs a delayed-choice test of the wave-particle complementary behavior. By combining the test results of each MZI, we understand comprehensively the wave-particle duality or complementarity, and where wave function collapse.

The key idea is that the output BS of each MZI, i.e., BS4, BS9, and BS11, can be inserted or removed respectively after a photon has entered the Extended-MZI.

4. Application of Extended-MZI

4.1. Effects of Removing or Inserting Output BSs of Extended MZI

The effects of removing or inserting output BSs of Extended MZI are shown in Table 1.

Table 1: Effects of Removing or Inserting Output BS

	Act: Removing or inserting output BS	Effects of Act on MZIs
BS4	Close ↔ open	First MZI: wave ↔ particle Second and Third MZI: to be determined experimentally
BS9	Close ↔ open	Second MZI: wave ↔ particle First and Third MZI: to be determined experimentally
BS11	Close ↔ open	Third MZI: wave ↔ particle First and Second MZI: to be determined experimentally

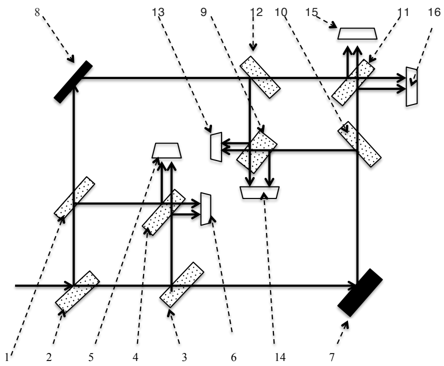
4.2. Wheeler-Delayed-Choice Experiment

The Extended-MZI can be applied to study Wheeler-Delayed-Choice Experiment (Fig. 5a and Fig. 5b). One may remove BS11 at three situations.

First situation: When a photon is between BS1 and BS2 (or between BS2 and BS3).

Second situation: When a photon is between BS1 and BS12 (or between BS3 and BS10).

Third situation: When a photon is between BS10 and BS11 (or between BS11 and BS12).



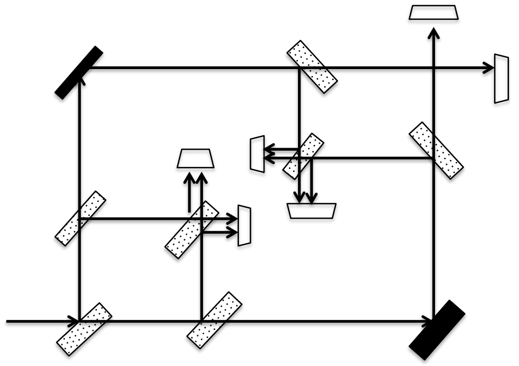


Fig. 5a Before removing BS 11 Fig. 5b After removing BS11

After removing BS11, we have two possible results:

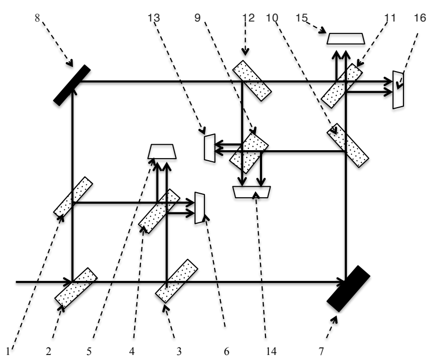
(1) The interference patterns *DISAPEARED* at the first, the second and the third MZIs, which imply that the information of removing BS11 has been sent all the way back to the source, and, thus that photons act like particle from very beginning.

(2) The interference patterns *STILL EXIST* at the first and the second MZIs, which imply that the information of removing BS11 has NOT been sent to BS10, BS12, BS1, and BS3, and that photons still act like wave. The wave functions of photons collapse, at least, after passing through BS10 and BS12.

4.3. Choice-Forwarded Experiment

Wheeler predicted that the act of removing or inserting output BS sends information backward to the source. With all of three output BSs, BS4, BS9 and BS11, in place, wave-behavior of photons shows in all three MZIs.

Now we ask whether the act of removing or inserting output BS sends information not only backward but also, at the same time, *forward*? To answer this question, we proposes a *Choice-forward* Experiment, i.e., insert or remove BS9 of Second MZI (Fig. 6a and Fig. 6b).



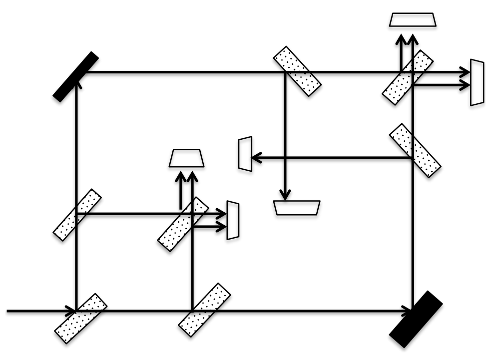


Fig. 6a Before removing BS9 Fig. 6b After removing BS9

We consider several situations:

(A) removing BS9 after photons into the first MZIs but before reaching BS1 and BS3, we test how the act of removing BS9 affects behavior of photons in two situations:

(A1) backward: how to affects the first MZI, whether prevent interference pattern from forming;

(A2) forward: how to affects the third MZI, whether preventing interference pattern from forming.

(B) removing BS9 after photons passing through BS1 and BS3, but before reaching BS12 and BS10, namely we already have interference pattern in the first MZI; we test how the act of removing BS9 affects behavior of photons in two situations:

(B1) backward: how to affects the first MZI, whether the previously existing interference pattern disappear;

(B2) forward: how to affects the third MZI, whether preventing interference pattern from forming.

(C) removing BS9 after photons passing through BS12 and BS10, but before reaching BS11, thus we already have interference patterns in the first MZI; the interference pattern in the second MZI disappeared; we test how the act of removing BS9 affects behavior of photons in two situations:

(C1) backward: how to affects the first MZI, whether the previously existing interference pattern disappear;

(C2) forward: how to affects the third MZI, whether preventing interference pattern from forming.

5. Alternative Configurations of Extended MZI

5.1. Alterative Version of Extended-MZI with Two MZIs

For simplicity, an Extended-MZI contains two MZIs (Fig. 7).

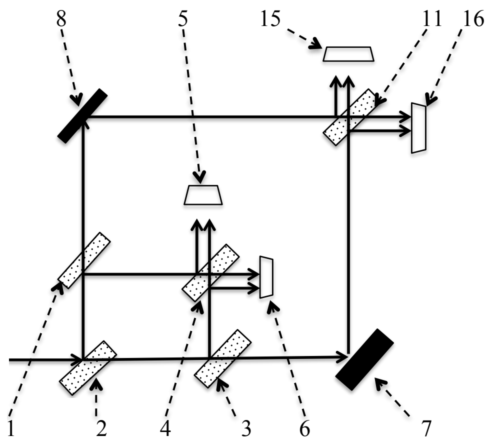


Fig. 7

By removing or inserting the output BS4, we can still perform the Wheeler-delayed-choice experiment and the choice-forward experiment proposed in this article.

5.2. Alternative Version of Extended-MZI with Entangled Photons

One can use an alternative source of photons. The BS2 and source of photons of Extended-MZI in Fig. 4 can be replaced by a source of entangled photons, which contains an argon laser, a nonlinear optical crystal BBO, and a Glan-Thompson prism, represented by “2” in Fig. 6, which emits entangled photons in two directions. Note there are no double slits.

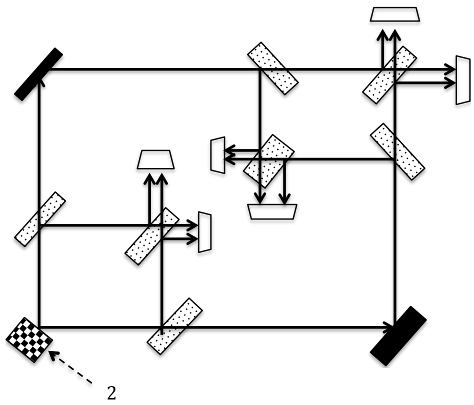


Fig. 8 Extended-MZI with Entangled Photons

This Version of Extended-MZI can be used to study the interactions between entangled photons.

5.3. Alternative Configurations of Extended MZI

On the other hand, since there are 3 MZIs, The configurations of experiments can be pre-setup, no need to make choice of output BSs. Namely we can do experiments with pre-set output BSs, either with or without output BSs, without either removing or inserting them. For the configurations with or without pre-set output BSs, we summarize in Table 2.

Table 2: Configurations with or without Output BSs

Configuration	BS4	BS9	BS11
A	First MZI: open	Second MZI: close	Third MZI: close
B	First MZI: open	Second MZI: open	Third MZI: close
C	First MZI: open	Second MZI: close	Third MZI: open
D	First MZI: open	Second MZI: open	Third MZI: open
E	First MZI: close	Second MZI: open	Third MZI: open
F	First MZI: close	Second MZI: close	Third MZI: open
G	First MZI: close	Second MZI: open	Third MZI: close
H	First MZI: close	Second MZI: close	Third MZI: close

In experiments, if all of open MZI show particle-like behavior, all of close MZI show wave-like behavior, we can conclude: (1) demonstrates Bohr's statement B; (2) disprove Bohr's statement A;

Illustrate those Configurations in Table 2 as below.

(A) Particle-wave-wave (Fig.9): BS4 is absent.

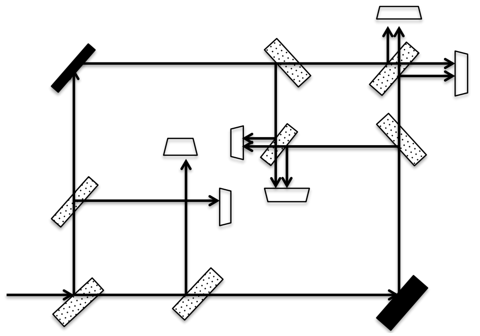


Fig. 9 Particle-wave-wave Version

(B) Particle-particle-wave (Fig.10): BS4 and BS9 are absent.

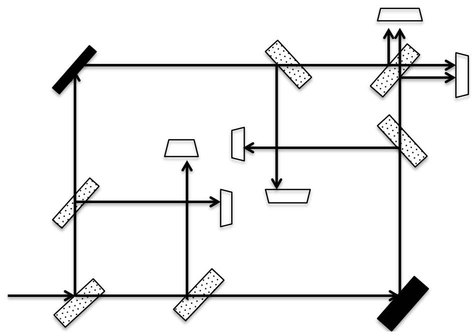


Fig. 10 Particle-particle-wave Version

(C) Particle-wave-particle (Fig.11): BS4 and BS11 are absent.

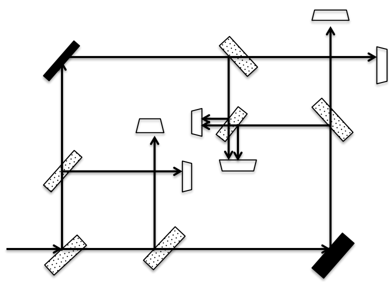


Fig. 11 Particle-wave-particle Version

(D) Particle-particle-particle (Fig.12): BS4, BS9 and BS11 are absent.

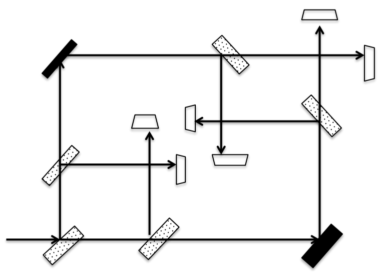


Fig. 12 Particle-particle-particle Version

(E) Wave-particle-particle (Fig.13): BS9 and BS11 are absent.

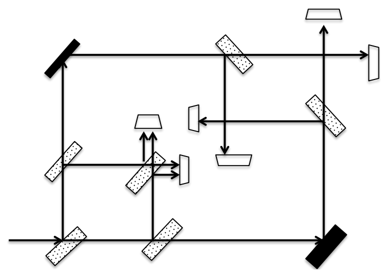


Fig. 13 Wave-particle-particle Version

(F) Wave-wave-particle (Fig.14): BS11 is absent.

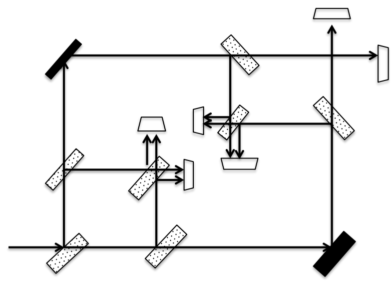


Fig. 14 Wave-wave-particle Version

(G) Wave-particle-wave (Fig.15): BS9 is absent.

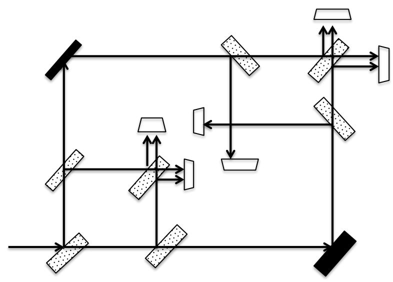


Fig. 15 Wave-particle-wave Version

6. Conclusion

We have proposed two powerful experimental tools, Cross-Double-Slits and Extended-MZI, for studying quantum phenomena, such as double-slit experiments, "which-way"-double-slit experiment, wave-particle duality, complementarity, causality, Wheeler-delayed-Choice experiment, information send backward in time, interactions between entangled photons. We propose a "Choice-forward" effect/experiment.

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Reference

(1) Y. Kim, et at., arXiv: quant-ph/9903047 (1999).

F. Kaiser, ArXiv: quant-ph/1206.4348 (2012).