# Double Slit to Cross Double Slit to Comprehensive Double Slit Experiments

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**Research Article**

**Keywords:** double slit experiment, cross double slit experiment, comprehensive double slit experiment, which way double slit, delayed choice experiment, causality, Bohm's trajectory theory

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# Double Slit to Cross Double Slit to Comprehensive Double Slit Experiments

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**Abstract**

Young's double slit experiments, which represent the mystery of quantum mechanics, have been interpreted by quantum probability waves and de Broglie-Bohm's trajectory/pilot waves. To study in detail, the double slit experiments are extended to the cross double slit experiments. We argue that an interpretation must be able to explain all of the double slit and cross double slit experiments consistently. To test the interpretations, the comprehensive double slit experiments have been performed, which challenge both the wave interpretation and the trajectory interpretation. The cross double slit experiments and comprehensive double slit experiments provide a new tool for studying the mystery of double slit, wave-particle duality, complementarity principle, wave theory and trajectory theory. In this article, we review the cross double slit experiments and comprehensive double slit experiments, and report new experiments.

**Keywords**: double slit experiment, cross double slit experiment, comprehensive double slit experiment, which way double slit, delayed choice experiment, causality, Bohm's trajectory theory

## 1. Introduction

The Young's double-slit experiment was performed in the year 1801 [1] [2], which, 100 years later, led to wave-particle duality. Feynman called it "a phenomenon […] has in it the heart of quantum mechanics. In reality, it contains the only mystery [of quantum mechanics]" [3]. Moreover, the nature of photons really puzzled Einstein. He wrote to M. Besso: "All these 50 years of conscious brooding have brought me no nearer to the answer to the question: What are light quanta?" [4].

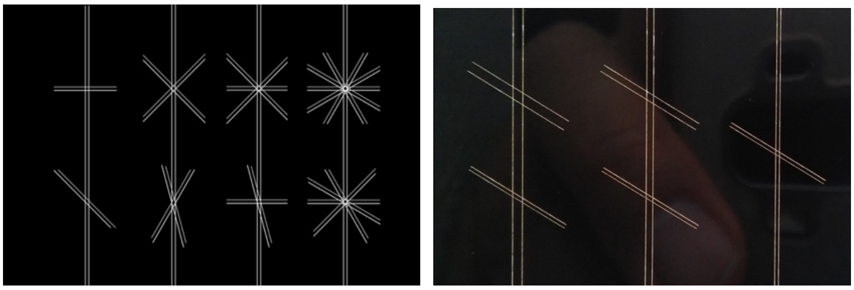
To explore the nature of photons further, Young's double-slit experiment was modified to which-way-double-slit experiment by observing which slit a photon would pass through. Once which slit a photon passing through is determined, the wave-like interference pattern disappears. The operational definition of "wave/particle" stands for "ability/inability to create interference" [5] [6] [7]. A variety of which way double slit experiments have been proposed and performed, such as double-double-slit experiment [8].

In 1978 and 1984, Wheeler proposed a series of thought experiments, delayed-choice experiments, which was designed to resolve the fundamental issues in quantum physics [9]. The standard interpretation of the MZI-delayed choice experiment states that photons made “retroactive decision”, which challenges the causality. A variety of delayed choice experiments have been proposed and performed, such as quantum eraser delayed choice experiment [10] [11].

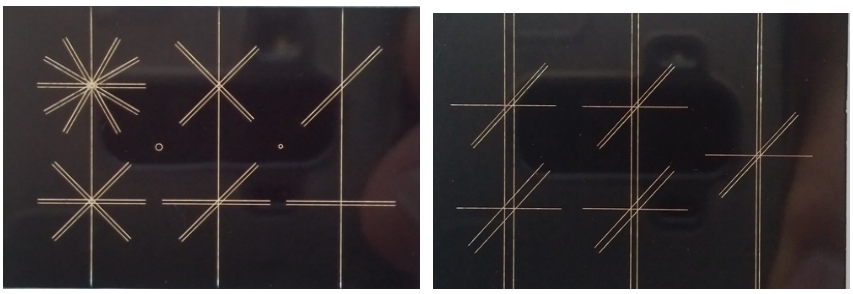
Recently, for studying the mystery of double slit experiments and testing the wave interpretation and trajectory interpretation, the cross-double-slit experiments [12] [13] and comprehensive double slit experiments [14] [15] [16] have been proposed/performed. In this article, we review the cross double slit and comprehensive double slit experiments, and report new experiments.

## 2. Cross Double Slit Experiments

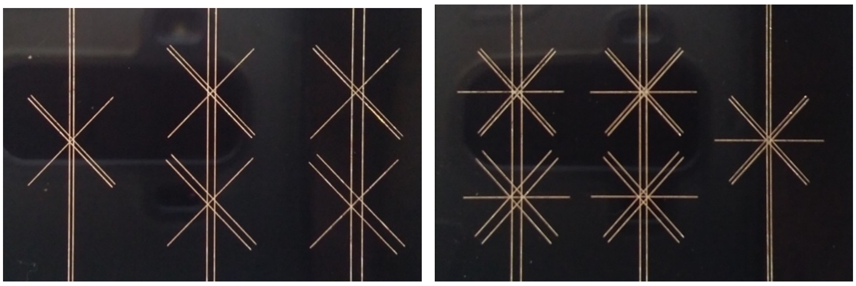
For studying the double slit experiments and wave-particle duality, the cross-double-slit experiments have been proposed/performed. The diaphragms (Figure 2.1) contain double-slit crossing double-slit, double-slit crossing triple-slit, single-slit crossing double-slit, single slit crossing triple-slit, and, hereafter, denoted all as “cross double slit”.



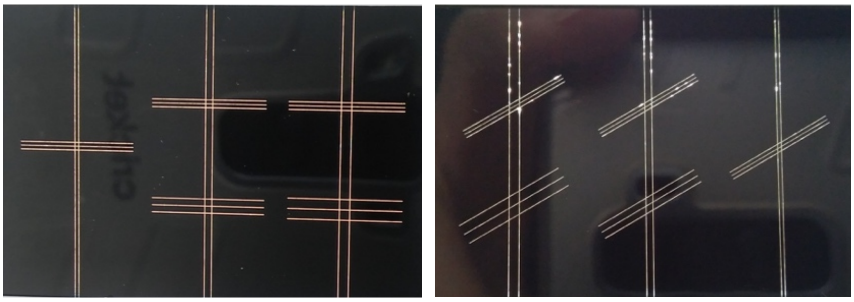
(a) Double slit crossing double slit: same/different spacing



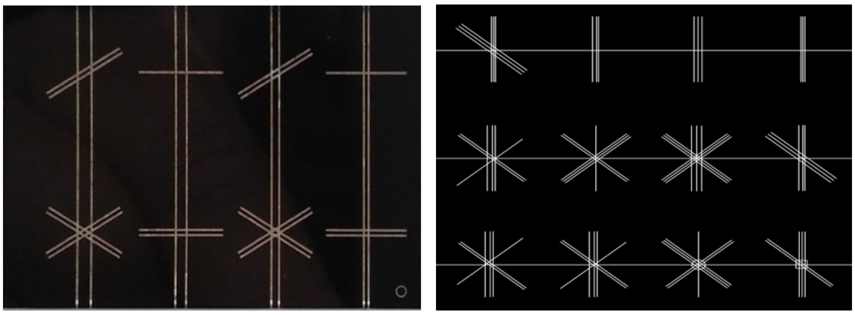
(b) Single slit crossing double slit: same/different spacing



(c) Single slit crossing double slit: same/different spacing



(d) Double slit crossing triple slit: same/different spacing



(e) Single slit/double slit crossing double slit/triple slit

Fig. 2.1 Diaphragms of cross-double slit

2.1. Double Slit Crossing Double Slit Experiments

2.1.1. Double Slit Crossing Double Slit: Same Spacing

The experimental setup of the cross double slit experiments consists of a laser source, a slide/diaphragm of cross double slit and a detector/screen. In the following experiments, we show the cross double slit and their interference patterns, which provide comprehensive data for building theoretical model. To clearly show the evolution from double slit experiments to cross double slit experiments, let us start with Young's double slit experiment (Figure 2.2).

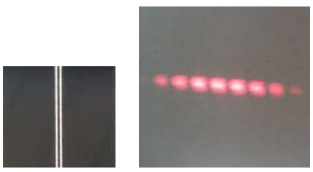


Figure 2.2 Young's double slit experiment

Experiment-2.1 (Figure 2.3): Double slit crossing double-slit and its interference pattern.

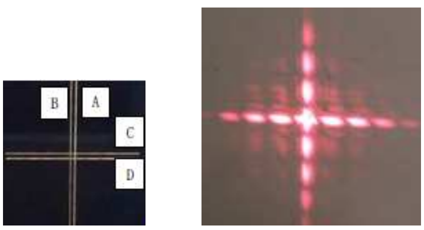



Figure 2.3

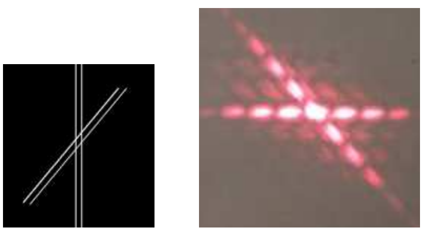


Figure 2.4

Experiment-2.2 (Figure 2.4): Tilt double slit crossing double-slit and its interference pattern.

Experiment-2.3 (Figure 2.5): Three double-slits crossing at the same spot and its interference pattern. The angle between the tilt double slit and the vertical double slit is 45 degree.

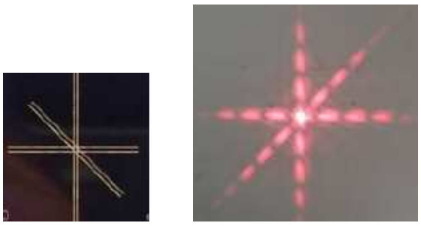


Figure 2.5

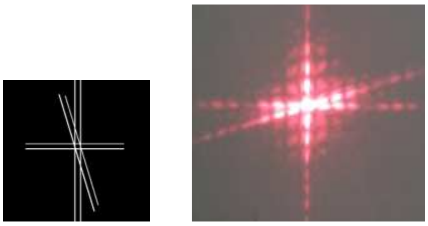


Figure 2.6

Experiment-2.4 (Figure 2.6): Three double-slits crossing at the same spot and its interference pattern.

The angle between the tilt double slit and the vertical double slit is 15 degree.

Experiment-2.5 (Figure 2.7)**:** Three double-slits crossing and its interference pattern.

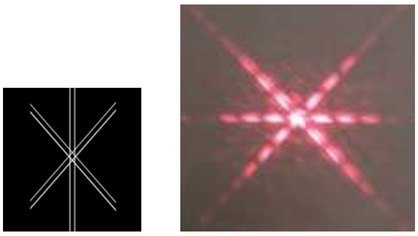


Figure 2.7

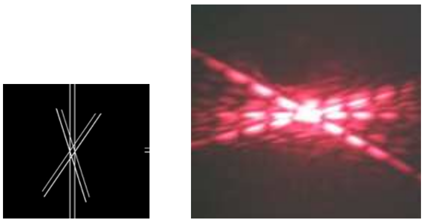


Figure 2.8

Experiment-2.6 (Figure 2.8): Three crossing double-slit and its interference pattern. The tilt angles are 15 and 30 degrees respectively.

Experiment-2.7 (Figure 2.9): Four crossing double-slit and its interference pattern.

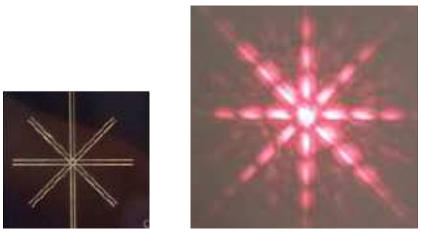


Figure 2.9

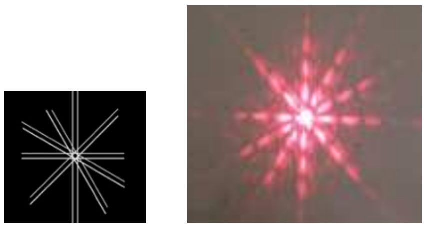


Figure 2.10

Experiment-2.8 (Figure 2.10): Five crossing double-slit and its interference pattern.

Experiment-2.9 (Figure 2.11): Six crossing double-slit and its interference pattern.

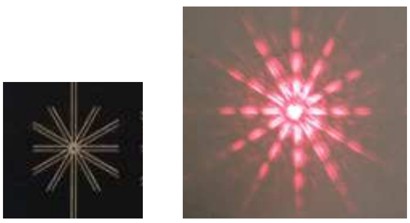


Figure 2.11

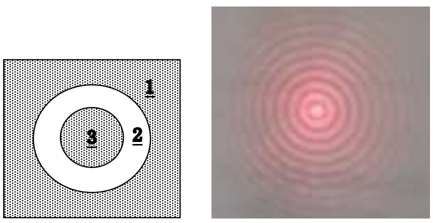


Figure 2.12

Experiment-2.10 (Figure 2.12): Rotation Invariance of double slit/cross double slit.

Combination of Figures 2.9, 2.10 and 2.11 suggests that double-slit and cross-double-slit have the rotation-invariance around its normal vector. If we increase the number of double-slits that are intersected at the same spot, the shape of the intersection will approach to a circular disc. To rotate either a double-slit or cross-double-slit around its normal vector, each slit is tangent to the intersection and forms disc-3 that is surrounded by ring-2. The final pattern can be obtained by either rotating the double-slit apparatus during experiment or by applying an apparatus of disc-3 with a diameter that is equal to the spacing between two slits, and ring-2 of the width that is equal to the width of a single-slit.

We argue that Figure 2.12 indicates that double-slit and cross-double-slit have the rotation-invariance around its normal vector.

2.1.2. Double Slit Crossing Double Slit: Different Spacing

Experiment-2.11 (Figure 2.13). Double slit crossing double slit of different spacing (the left of Figure 2.13) and its interference pattern (the right of Figure 2.13).

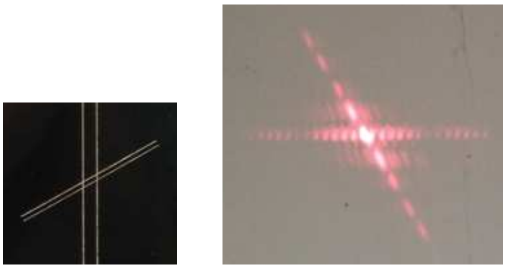


Figure 2.13

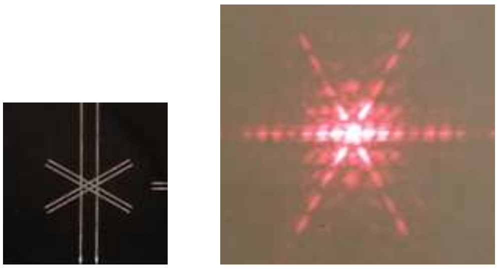


Figure 2.14

Experiment-2.12 (Figure 2.14): Double slit crossing double slit of different spacing and its pattern.

Conclusion: it is a challenge to consistently interpret the experiments in Section 2.1.

2.2. Double-Slit Crossing Triple-Slit Experiments

A typical triple slit and its pattern show below.

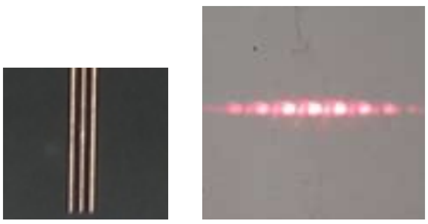


Figure 2.15 Triple slit and its interference pattern

2.2.1. Double-Slit Crossing Triple-Slit Experiments: Same Spacing

Experiment-2.13 (Figure 2.16): Double slit crossing triple slit and its interference pattern. All of spacing between slits are 0.25 mm.

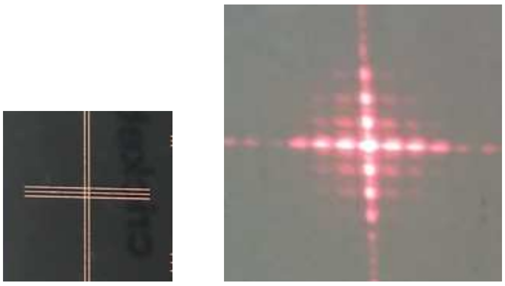


Figure 2.16

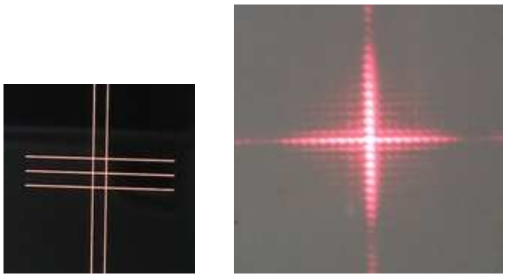


Figure 2.17

Experiment-2.14 (Figure 2.17): Double slit crossing triple slit. Spacings between slits are 0.75 mm.

Experiment-2.15 (Figure 2.18): Double slit crossing tilt triple slit. Spacings between slits are 0.25 mm.

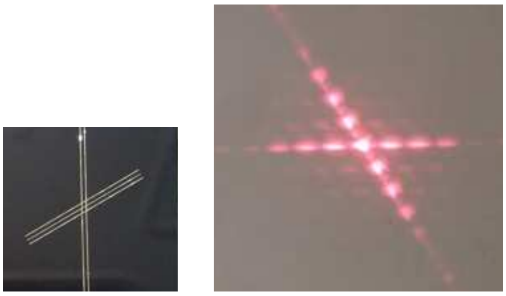


Figure 2.18

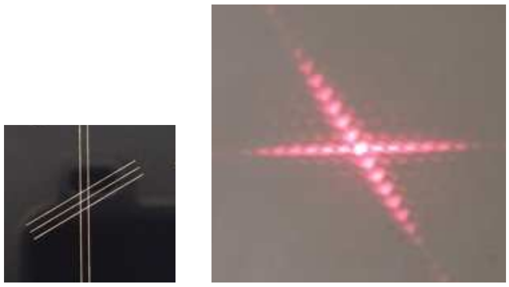


Figure 2.19

Experiment-2.16 (Figure 2.19): Double slit crossing tilt triple slit. Spacings between slits are 0.5 mm.

2.2.2. Double-Slit Crossing Triple-Slit Experiments: Different Spacing.

Experiment-2.17 (Figure 2.20): Spacing between two vertical slits is 0.5 mm, and the spacing between three horizontal slits is 0.25 mm.

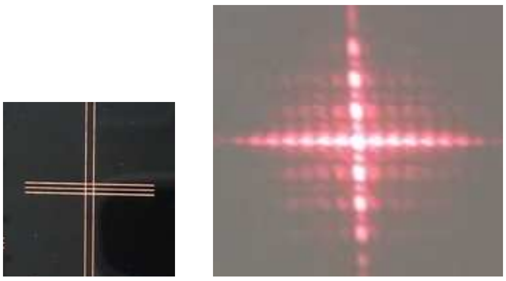


Figure 2.20

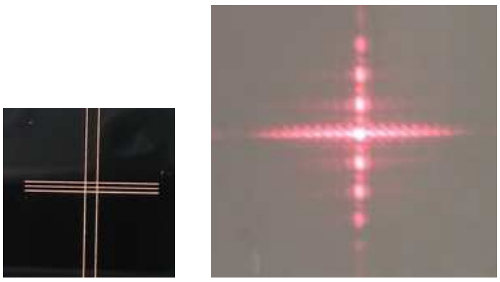


Figure 2.21

Experiment-2.18 (Figure 2.21): The spacing between two vertical slits is 0.75 mm, and the spacing between three horizontal slits is 0.25 mm.

Experiment-2.19 (Figure 2.22): The spacing between two vertical slits is 0.5 mm, and the spacing between two of three tilt slits is 0.25 mm.

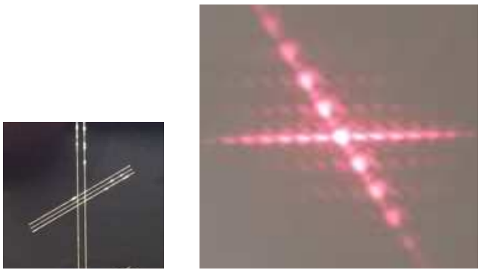


Figure 2.22

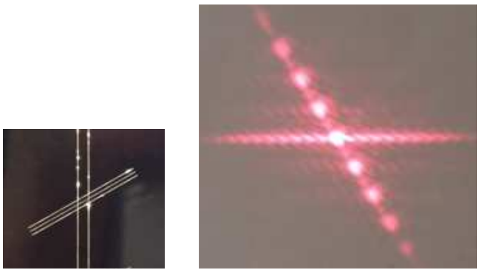


Figure 2.23

Experiment-2.20 (Figure 2.23): The spacing between two vertical slits is 0.75 mm, and the spacing between three tilt slits is 0.25 mm.

Conclusion: it is a challenge to consistently interpret the experiments in Section 2.2.

2.3. Which Way Cross Double Slit Experiments: Single-Slit Crossing Double-Slit

To explore the nature of photon further, 1D-double-slit experiment was extended to which-way-1D-double-slit experiment. Technically feasible realizations of which-way experiment were proposed in the 1970s [17] [18]. A photon is observed near a slit by utilizing a photoelectric-detector to register the photon, practically it blocks the paths of photons, namely equivalent to cover a slit [19] [20]. When the photon is detected, the interference pattern disappears.

We argue that, if we shift the focus from detecting photons to observe the patterns, then to cover a slit of a double slit apparatus is equivalent to use a single slit apparatus, namely,

*) Observing photons at a slit is equivalent to block photons passing through the slit;

*) To block photons passing through a slit is equivalent to cover that slit;

*) To cover a slit is equivalent to using a single slit instead using double slit and covering one

Thus, for doing which way experiments with diaphragm of cross double slit, we make one of double slits as a single slit.

2.3.1. Which Way Cross Double Slit Experiments: Same Spacing

Figure 2.24 shows the standard which way experiment, where the left drawing is the double slit with an "observer" at slit "A", the right is the pattern. Figure 2.25 shows the which way cross double slit.

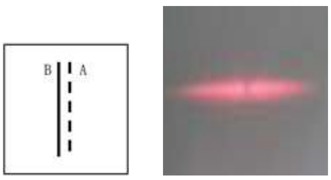



Figure 2.24

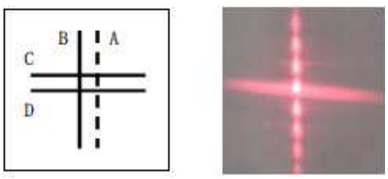



Figure 25

The significant difference is that for the standard which way experiment, they must go through slit "B", while for which way cross double slit experiment, if photons do not go through slit "A", photons can go through either slit “B” or “C” or “D”.

Experiment-2.21 (Figure 2.26): Single-slit crossing double-slit.

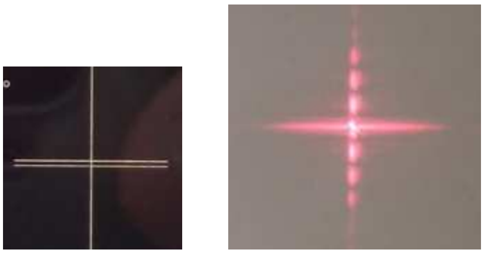


Figure 2.26

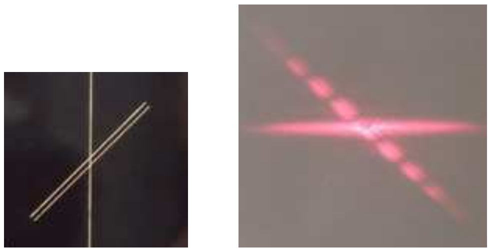


Figure 2.27

Experiment-2.22 (Figure 2.27): Single-slit crossing tilt double-slit

Experiment-2.23 (Figure 2.28): Single slit crossing two double slits with same spacing.

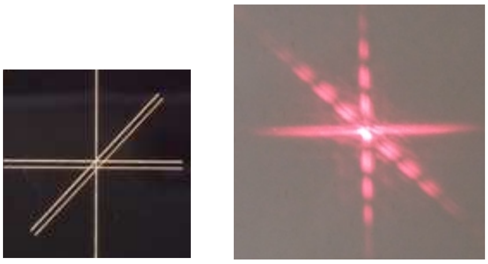


Figure 2.28

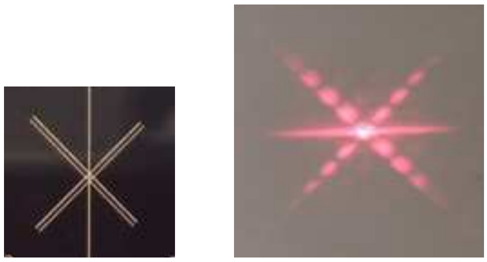


Figure 29

Experiment-2.24 (Figure 2.29): Single slit crossing two tilt double slits of same spacing.

Experiment-2.25 (Figure 2.30): Single slit crossing three double slits of same spacing.

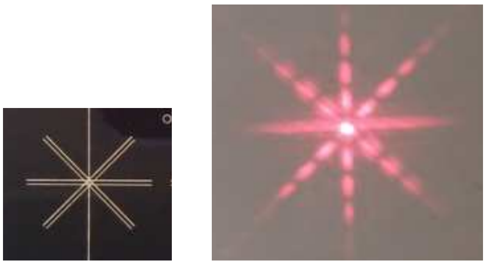


Figure 2.30

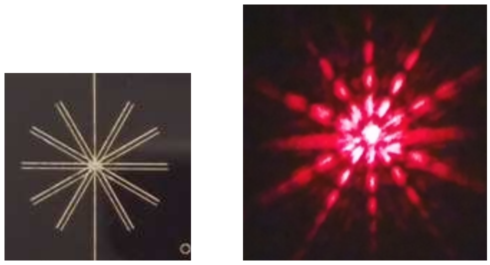


Figure 2.31

Experiment-2.26 (Figure 2.31): Single slit crossing five double slits of same spacing.

2.3.2. Which Way Double Slit Experiments: Different Spacing

Experiment-2.27 (Figure 2.32): Single slit crossing two double slits with different spacings.

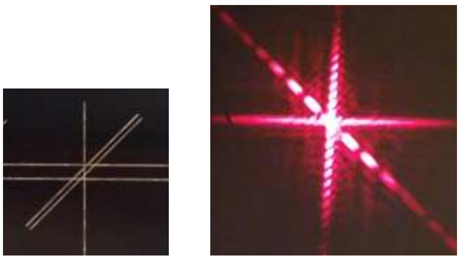


Figure 2.32

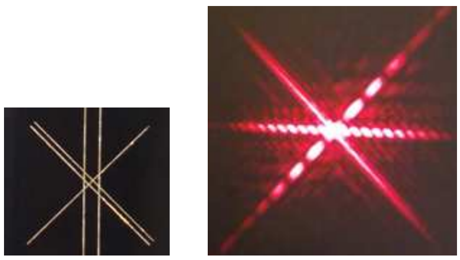


Figure 33

Experiment-2.28 (Figure 2.33): Single slit crossing two double slits with different spacings.

Experiment-2.29 (Figure 2.34): Single slit crossing three double slits with different spacings.

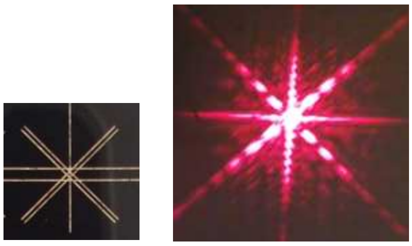


Figure 2.34

2.3.3. Which Way Double Slit Experiments: Triple Slit

Experiment-2.30 (Figure 2.35): Single slit crossing triple slit (narrower spacing)

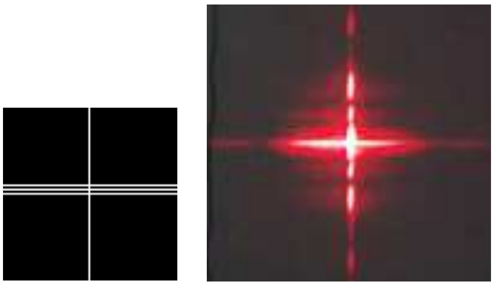


Figure 2.35

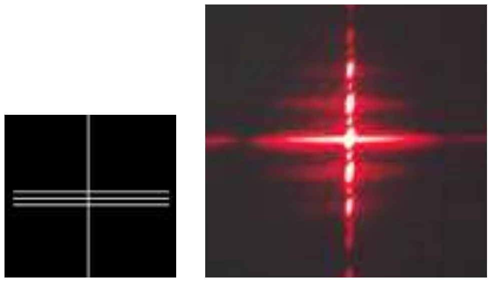


Figure 2.36

Experiment-2.31 (Figure 2.36): Single slit crossing triple slit (wider spacing)

Experiment-2.32 (Figure 2.37): Single slit crossing triple slit of non-uniform spacing.

Figure 2.37

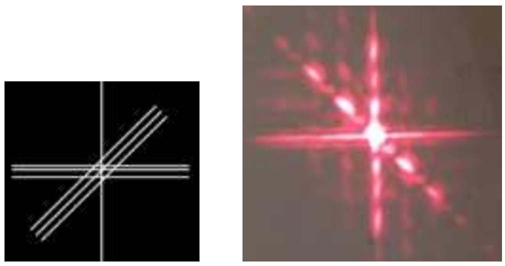


Figure 2.38

Experiment-2.33 (Figure 2.38): Single slit crossing two triple slit of different/non-uniform spacing.

Experiment-2.34 (Figure 2.39): Two single slits crossing double slit and triple slit of different spacing.

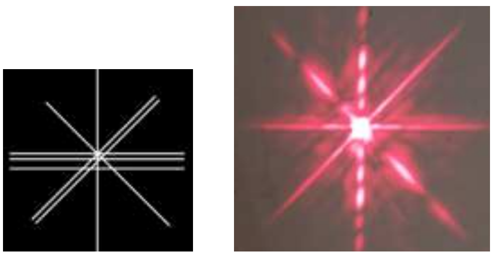


Figure 2.39

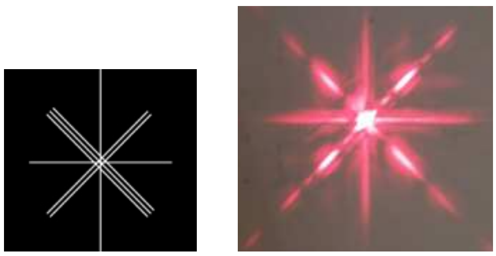


Figure 2.40

Experiment-2.35 (Figure 2.40): Two single slits crossing double slit and triple slit of same spacing.

Conclusion: it is challenge to interpret the experiments in Section 2.3 consistently.

2.4. Delayed Choice Cross Double Slit Experiments

The standard MZI version of the delayed choice experiment is shown below. The standard interpretation is the following: Figure 2.41(a) shows an open-MZI, photons are detected by D1 and D2*, and* behave the same, as particles, *from the time of its emission to the time of its detection*.

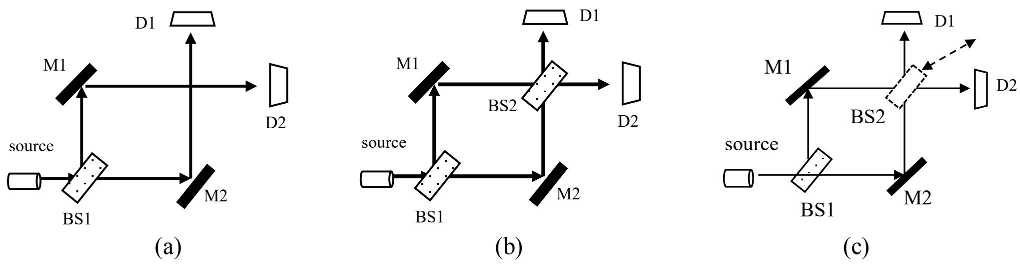



Figure 2.41 Standard MZI-version of Delayed Choice Experiment

For a closed-MZI (Figure 2.41b), before arriving at and after reflected by BS2 or passing through BS2, photons behave the same, as waves, *from the time of its emission to the time of its detection.* The dashed BS2 in Figure 2.41c indicates removing/inserting the BS2 when a photon is flying, which causes difficulty to perform the delayed choice experiment. The standard interpretation of the MZI-delayed choice experiment (Figure 2.41c) is: when a photon is flying, inserting BS2, the photon would behave as wave before arriving at the position of BS2 as BS2 were there; namely, photons would behave as wave *from the time of its emission to the time of its detection*, even there was no BS2 at the time of its emission, which challenges the causality; it states that photons made "retroactive decision".

2.4.1. Rule-1, Rule-2 and Postulate-1

For analyzing delayed-choice phenomena, we propose and test two rules and postulate-1. Then in Section 3, we propose and test Postulate-2.

Rule-1: When a single input beam of photons travelling as particle strikes a BS, reflection and transmission attributed to BS do not change photons' behavior, namely, before and after reflection and transmission, photons behave as particles.

Example: when a beam of photons outputted from a BS behaves as particles, then the input beam of photons behaves as particles, while the other output beam of photons behaves as particles.

Rule-2: When a beam of photons travelling as waves strike a BS, reflection and transmission attributed to BS do not change photons' behavior, namely, before and after reflection and transmission, photons distribute as waves.

Postulate-1: Before passing through a slide/diaphragm of double slit/cross-double slit, photons behave as particles.

Note that, hereafter, for clearly show the results of experiments and draw conclusions, we arrange apparatuses to show the patterns, created by photons passing through different paths, on a same big screen/detector, a long white board.

We demonstrate Rule-1, Rule-2 and Postulate-1 experimentally first.

Experiment-2.36 (Figure 2.42): Testing Rule-1

Experimental setup: A laser source emits photons that are partially reflected by BS1 and arrive at detector1 (D1), and partially transmitted though BS1 and arrive at D2. To show the patterns, we replace two individual detectors by a bigger detector (Figure 2.42a).

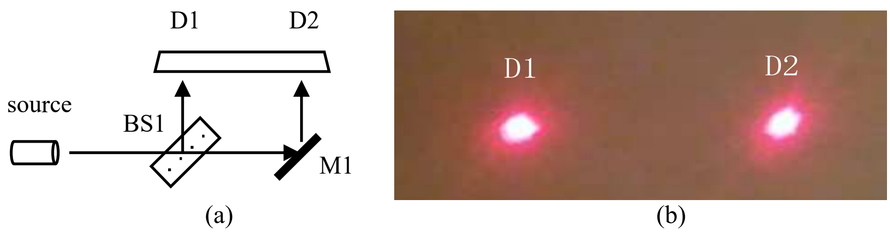



Figure 2.42 Testing Rule-1

Observation (Figure 2.42b): both D1 and D2 show the images of the source.

Conclusion: Rule-1 is proved. Photons detected on both D1 and D2 have the same particle nature. Namely the particle nature is not changed by either reflected by BS or passing through BS.

Experiment-2.37 (Figure 2.43): Testing Rule-2

Experimental setup: A laser source emits photons that travel through a slide of cross double slit. Then, the photons are partially reflected by BS1 and partially transmitted through BS1, and arrive D1 and D2 respectively (Figure 2.38a). The slide is a cross double slit.

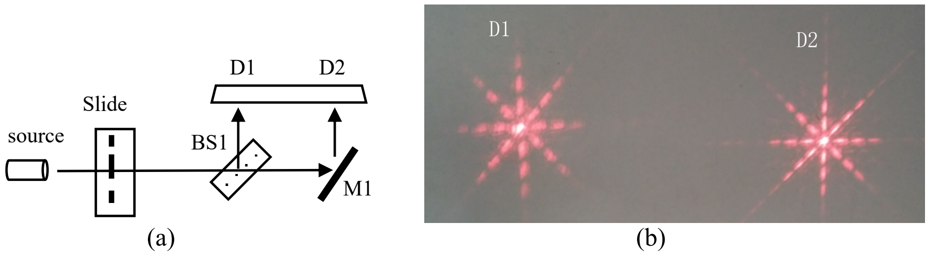



Figure 2.43 Testing Rule-2

Observation (Figure 2.43b): D1 and D2 show the same interference patterns.

Conclusions: Rule-2 is proved. Removing the slide, experiment-2.37 becomes experiment-2.36, which implies that it is the slide that affects photons' behavior. Combination of Rule-1 and Rule-2 shows that BS does not affect the behavior of a single input beam of photons, which leads to Postulate-1.

We perform two experiments to test Postulate-1 (Experiment-2.38 and Experiment-2.39).

Experiment-2.38 (Figure 2.44): Testing Postulate-1

Experimental setup (Figure 2.44a): Photons passing through BS1 and slide arrive at D2. Photons reflected by BS1 arrive at D1.

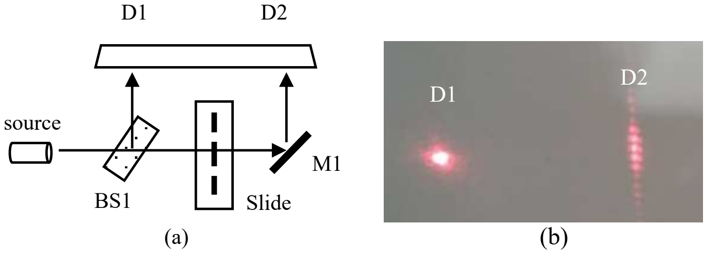



Figure 2.44. Testing Postulate-1 (1)

Observations (Figure 2.44b): (1) D1 shows the image of source; (2) D2 shows an interference pattern of double slit.

Conclusion: D1 shows the particle nature of photons. Based on Rule-1, photons passing through BS1 towards slide behave as particle as well, namely before arriving at slide, photons behave as particle. Postulate-1 is proved.

Experiment-2.39 (Figure 2.45): Testing Postulate-1

Experimental setup (Figure 2.45a): Photons travelling through BS1 and BS2, reflected by M2 and strike at D2. Photons reflected by BS1 and passing through slide-1 strike at D1. Photons reflected by BS2/M1/M3, and then passing through slide-3 strike at D3. To show the difference, we use a cross-double slit for slide-1 and a double slit for slide-3.

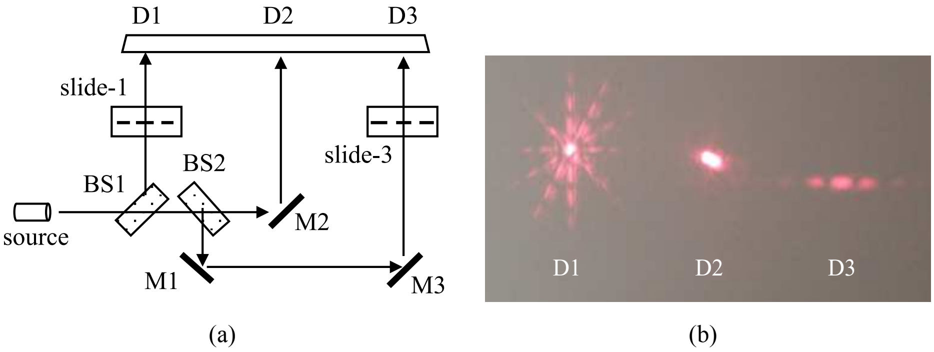



Figure 2.45 Testing Postulate-1 (2)

Observations (Figure 2.45b): D2 displays the image of the source, i.e., photons passing through BS1 and BS2 behave as particles.

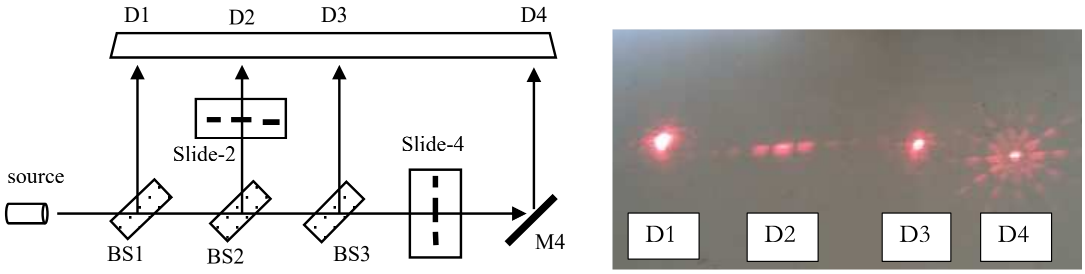
Conclusion: Thus, according to the Rule-1, photons reflected by BS1 and BS2/M1/M3 traveling towards slide-1 and slide-3, respectively, behave as particles. Namely, photons behave as particles before arriving double slit/cross-double slit. Postulate-1 is proved.

On the other hand, D1 and D3 show interference patterns. Particle nature and wave distribution coexist in “the same experiment”. For studying wave-particle duality and complementarity principle, let's define the term, "the same experiment", as: when there is "only one source" emitting light/photon, regardless configurations of experimental apparatus, the experiment is defined as the same experiment.

2.4.2. Modified Delayed Choice Double Slit Experiments

Experiment-2.40 (Figure 2.46): delayed choice double slit experiment (1)

Experimental setup (Figure 2.46a): Photons passing through BS1/BS2/BS3 and slide-4 arrive at D4. Photons reflected by BS1 arrive at D1; photons reflected by BS2 pass through slide-2 and arrive at D2; photons reflected by BS3 arrive at D3.



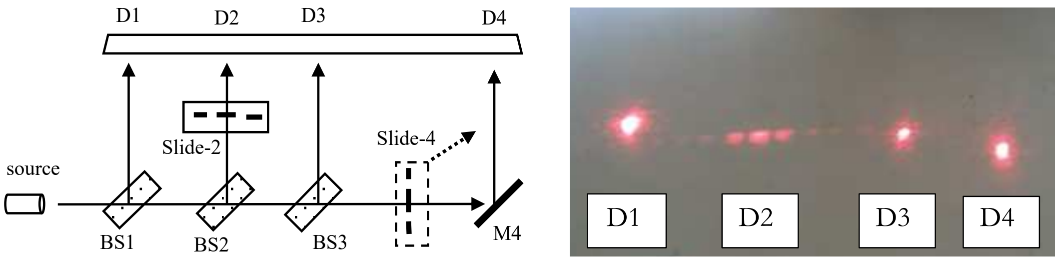

.(a) (b)

Figure 2.46 Double slit version of delayed choice experiment (1)

Observations (Figure 2.46b): D1 shows the image of the source; D2 displays wave distribution; D3 shows the image of the source; D4 displays wave distribution.

Experiment-2.41 (Figure 2.47): Double slit delayed choice experiment (2)

Experimental setup (Figure 2.47a): removing slide-4 (denoted as dashed slide-4 and dashed arrow).



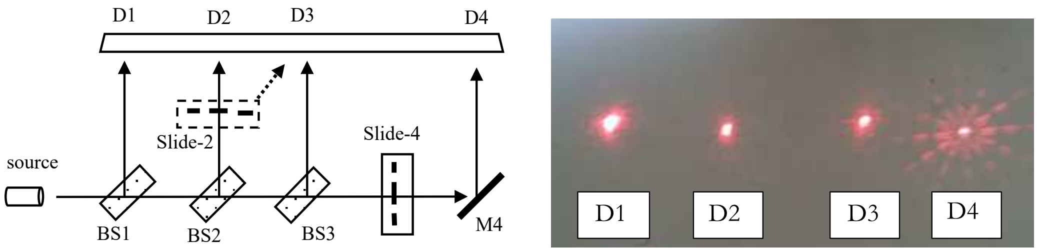

.(a) (b)

Figure 2.47 Double slit version of delayed choice experiment (2)

Observations (Figure 2.47b): D4 shows images of source; D1 and D3 still show the particle patterns; D2 still shows wave distribution.

Experiment-2.42 (Figure 2.48): Double slit delayed choice experiment (3)

Experimental setup (Figure 2.48a): removing slide-2




(a) (b)

Figure 2.48 Double slit version of delayed choice experiment (3)

Observations (Figure 2.48b): D2 shows the image of source; D1 and D3 still show particle nature of photon; D4 still show the wave patterns.

Conclusions: comparing Experiment-2.40, -2.41 and -2.42:

(1) Based on Rule-1, photons passing through B1 and B3 behave as particle, thus, before arriving slide-2 and slide-4, photons behave as particle respectively.

(2) Slide-2 and slide-4 convert photons' particle behavior (before arriving) to wave distribution (after passing through) respectively. The slide determines the behavior of photons only when photons passing through it, but not behavior before passing it. Thus, slide-2 and slide-4 can be removed any time during experiment, which makes the delayed choice experiments easier to be performed.

(3) Particle nature and wave distribution coexist in the same experiment.

(4) There is no retroactive decision phenomenon. The standard interpretation of the delayed choice experiments is challenged at the macroscopic level.

It would be interesting to perform the experiment by emitting photons one at a time.

### 2.4.3. Modified-MZI Version of Delayed Choice Experiments

In the interpretations of delayed-choice experiments, photon is described as a "person" to "decide" its own behavior. To explore the interpretations further by MZI configurations, we combine the MZI and double slit/cross double slit in the same delayed choice experiment. The purposes of experiments of this section are to test: (1) whether photons behave differently when traveling along different paths; (2) whether photons behave differently when traveling along the same path; (3) what determines the behaviors of photons under the circumstances of with and without an output BS.

To be able to visually observe the experimental result, we modify the MZI delayed choice experiment by replace BS2 with a slide of double slit and/or cross double slit.

Experiment-2.43-open (Figure 2.49): modified MZI delayed choice experiment (1)

Experimental Step: Figure 2.49a is a standard open-MZI. We modified MZI as shown in Figure 2.49b.

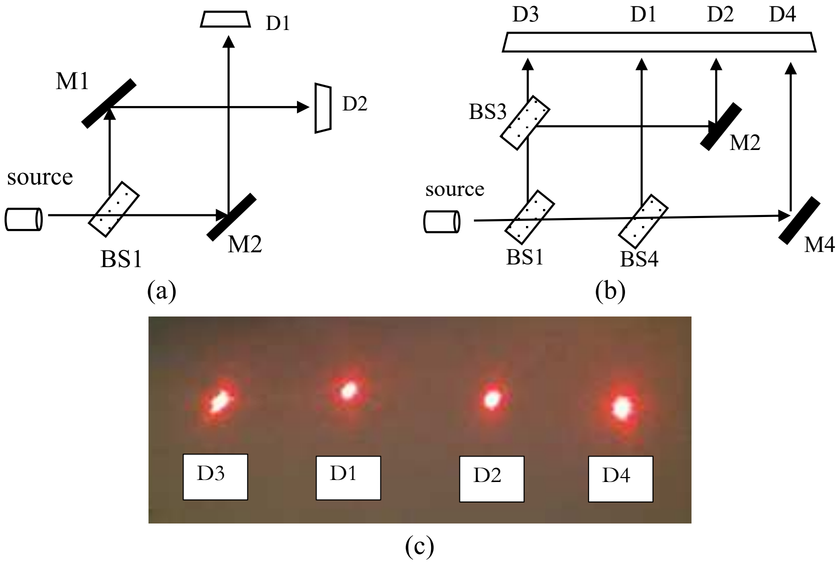



Figure 2.49-open Modified MZI delayed choice experiment (1)

To study the behavior of photons travelling along the path of source-BS1-M1-D2 and source-BS1-M2-D1, M1 and M2 are replaced by BS3/D3 and BS4/D4 respectively (Figure 2.49b).

Observation (Figure 2.49c): All detectors show the images of the source.

Experiment-2.44-close (Figure 2.50): Modified MZI delayed Choice experiment (1)

Experimental Setup (Figure 2.50a): inserting slide-1.

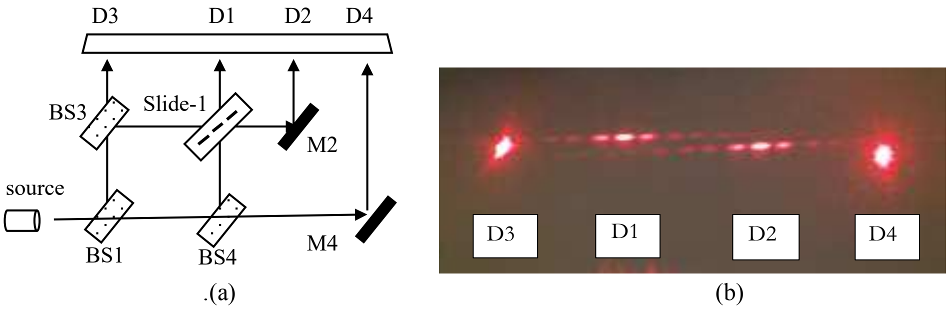


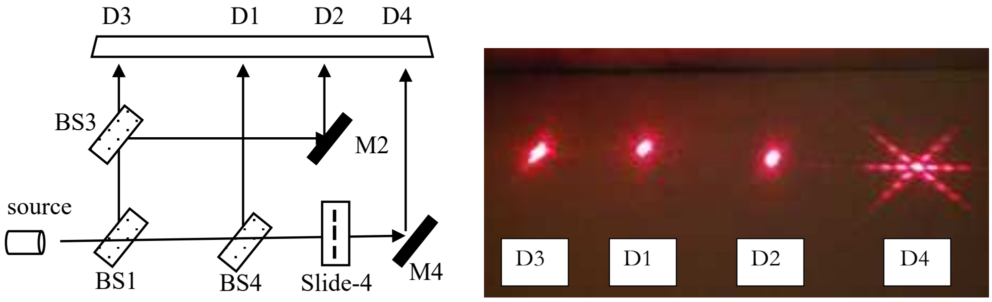

Figure 2.50 Modified MZI delayed choice experiment (1)

Observation (Figure 2.50b): D3 and D4 still show the images of the source, while D1 and D2 show the wave distribution of photons.

Conclusion: to remove/insert slide-1 does not affect the behavior of photons arriving D3 and D4.

Experiment-2.45-open (Figure 2.51): Modified MZI delayed choice experiment (2)

Experimental Setup: adding slide-4 between BS4 and M4 (Figure 2.51a).

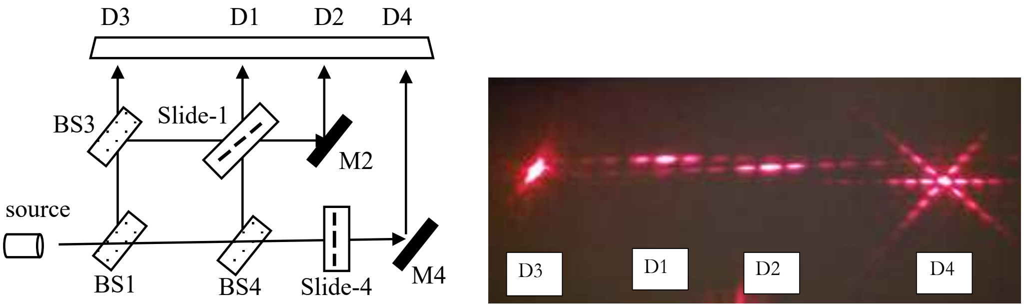



.(a) (b)

Figure 2.51 Modified MZI delayed choice experiment (2)

Observation (Figure 2.51b): D1, D2, D3 still show the images of the source, while D4 shows the wave distribution due to slide-4.

Experiment-2.45-closed (Figure 2.52)**:** Modified MZI delayed choice experiment (2)




. (a) (b)

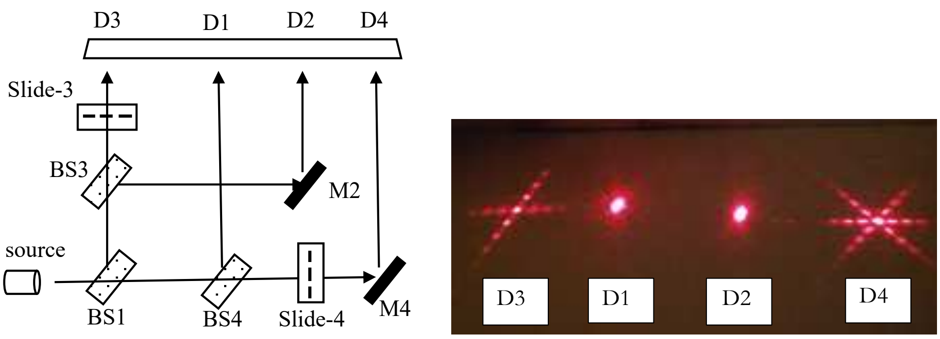
Figure 2.52 Modified MZI delayed choice experiment (2)

Observation (Figure 2.52b): D3 and D4 still show the same image of the source and the wave distribution, while D1 and D2 show the wave distribution due to slide-1.

Conclusion: Experiment-2.40-open/closed show that the removing/inserting slide-1 does not affect the behavior of photons arriving D3 and D4 and thus no retroactive phenomena.

Experiment-2.46-open (Figure 2.53)**:** Modified MZI delayed choice experiment (3)

Experimental setup (Figure 2.53a): Similar to that shown in Figure 2.51a, additionally inserting slide-3 between BS3 and D3.

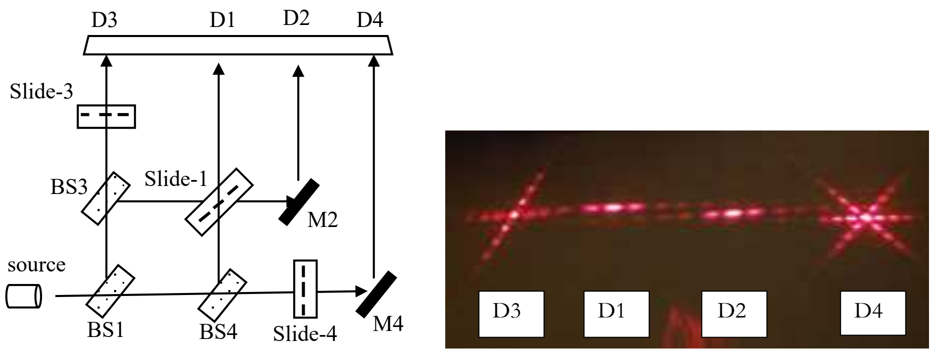



. (a) (b)

Figure 2.53 Modified MZI delayed choice experiment (3)

Observation (Figure 2.53b): D1 and D2 show the image of the source, while D3 and D4 show the wave distributions due to slide-3 and slide-4 respectively.

Experiment-2.46-closed (Figure 2.54)**:** Modified closed-MZI delayed choice experiment (3)




. (a) (b)

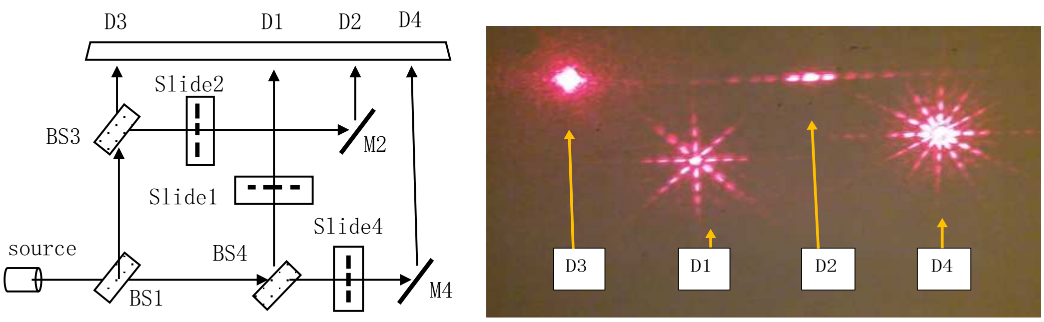
Figure 2.54 Modified MZI delayed choice experiment (3)

Experimental setup (Figure 2.54a): inserting slide-1 between BS3 and M2.

Observation (Figure 2.54b): D3 and D4 still show the same wave distribution patterns, while D1 and D2 show the wave distribution due to the slide 1.

Conclusion: To remove/insert slide-1 does not affect the behavior of photons detected by D3/D4. Thus, experiments-2.44 to 2.46 challenge the retroactive interpretation of delayed choice experiments.

Experiment-2.47-closed (Figure 2.55): Placing slide2 between BS3 and M2/D2, slide1 between BS4 and D1, slide4 between BS4 and M4/D4 (Figure 2.55a). We referred it as Modified-closed-MZI.

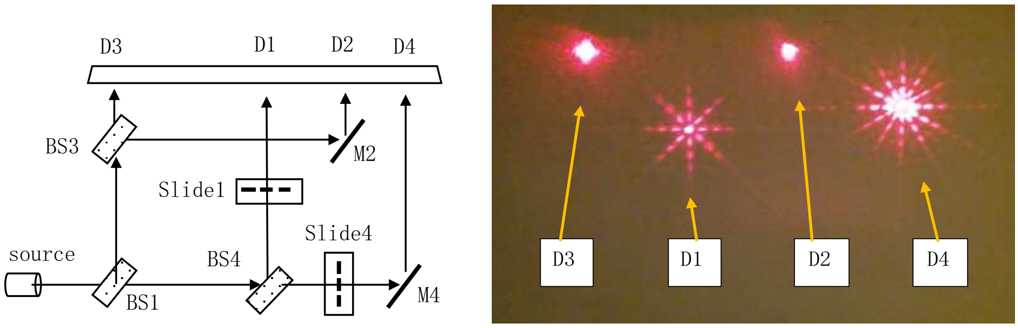



. (a) (b)

Figure 2.55 Modified-closed-MZI and patterns

Observation (Figure 2.55b): D3 shows the image of the source; while D1, D2 and D4 show the interference patterns created by slide1, slid2 and slide4 respectively, so photons distribute as wave.

Experiment-2.47-half-open-1 (Figure 2.56a)**:** remove slide 2. We referred it as half open.

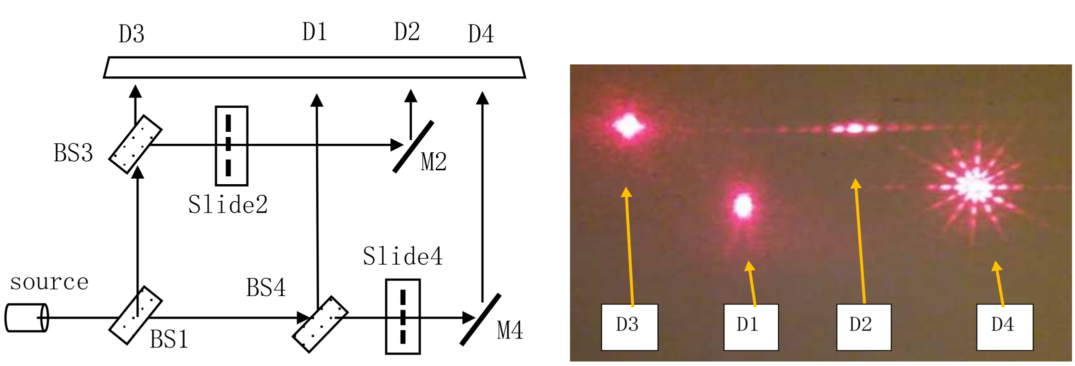



.(a) (b)

Figure 2.56: Removing slide 2

Observation (Figure 2.56b): D2 and D3 show the image of the source. D1 and D4 show wave distributions respectively determined by slide1 and slide4.

Experiment-2.47-half-open-2 (Figure 2.57)**:** removing slide1 (Figure 2.57a), referred it as half open.




. (a) (b)

Figure 2.57

Observation (Figure 2.57b): D3 and D1 show the image of the source. D2 and D4 show wave distributions respectively determined by slide2 and slide4.

Conclusions: Slide 1 and slide 2 only change the behaviors of photons passing through them, but not the behaviors of photons not passing through them. Thus, slide 1 and slide 2 can be removed/inserted any time and without affect the behaviors of photons traveling along different paths. Photons behave independently when traveling along each path. Namely, the removing/inserting a slide does not affect the behavior of photons traveling along the other paths, and does not affect the behavior of photons before arriving the slide of double slit. Although the photons are emitted by the same source, the behaviors of photons traveling along the same path are different before and after passing the slide. Therefore, the present does not determine the past retroactively, but determines the future.

The modified-MZI delayed choice experiments can be performed without sophisticated equipment. The conclusion of the experiments can be observed by naked eye.

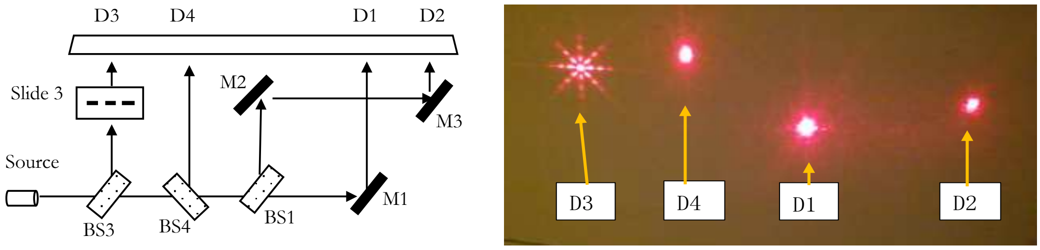
The double slit experiments are extended to the cross double slit experiments that is more complex. We suggest that an interpretation must be able to explain all of double slit and cross double slit experiments consistently.

2.4.4. Testing Interpretation of Delayed-choice Experiment

Now, we modify the closed-MZI to test the interpretation that states that, when a photon is flying, inserting BS2, photons would behave as wave *from the time of its emission to the time of its detection*, even there was no BS2 at the time of its emission. The key is to test whether photons behave the same before arriving the position of BS2 for the situations of both with and without BS2. For visual observation, we replace BS2 with two slides of double slit/cross double slit.

Experiment-2.48-open (Figure 2.58): Modified-open-MZI delayed choice experiment.

Experimental Setup: we insert BS3/slide3/D3 and BS4/D4 between the source and BS1 (Figure 2.58a).



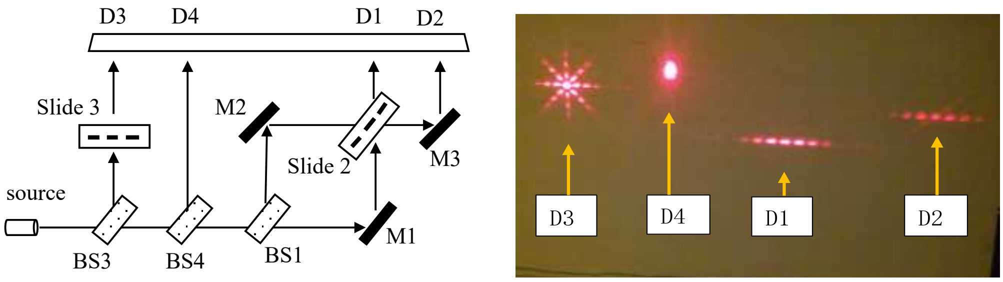

.(a) (b)

Figure 2.58 Modified MZI delayed choice experiment (4)

Observation (Figure 2.58b): D3 shows the wave distribution due to slide 3, D4 shows the image of source, while D1 and D2 show the images of source.

Experiment-2.48-closed (Figure 2.59): Modified-closed-MZI delayed choice experiment.

Experimental Setup: For visually observing the experimental results, place slide 2 of double slit at 45 degree. Arranging all detectors, D1, D2, D3 and D4, on the same big screen (Figure 2.59a).



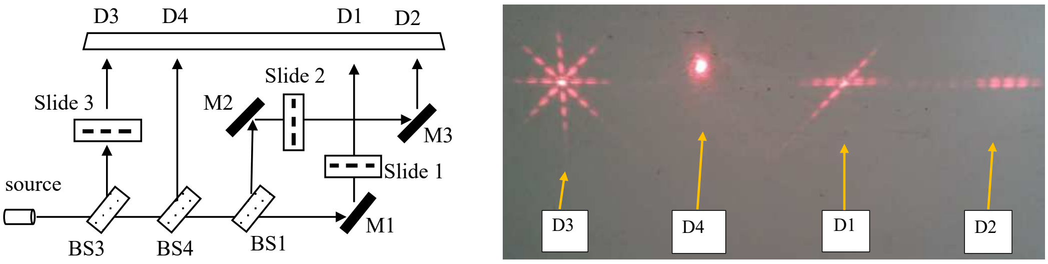

. (a) (b)

Figure 2.59 Modified-closed-MZI and patterns

Observation (Figure 2.59b): D3 still shows the interference pattern created by slide3, while D4 still shows the image of the source. D1 and D2 show the interference pattern created by slide 2. The patterns on D1/D2 are changed from the images of the source to wave distributions.

Conclusion: to remove/insert silde2 does not determine the behavior of photons from the source to BS1, namely does not determine the behaviors of photons retroactively. Although, to remove/insert silde2 does change the behaviors of photons after passing through slide2. Take into account Postulate-1, slide 2 can be removed/inserted at any time during experiment and no need to emit photons one at a time. Particle nature and wave distribution coexist in the same experiment.

Experiment-2.49-closed (Figure 2.60): Modified-closed-MZI delayed choice experiment.
Experimental Setup: an alternative configuration is shown in Figure 2.60. We place slide 2 between M2 and M3, and slide 1 between M1 and D1.




. (a) (b)

Figure 2.60 Modified-closed-MZI and patterns

Figure 2.60b shows that each pattern is created independently and thus, not affect by what happens in other paths.

Conclusion: it is a challenge to consistently interpret the experiments in Section 2.

## 3. Comprehensive Double Slit Experiment

### 3.1. Model and Two Postulates

To study the double slit experiments, we introduced the model and two postulations [14] [15].

*) Model: the diaphragm of double slit and its right-side neighborhood is represented as a “virtual box” (Figure 3.1).

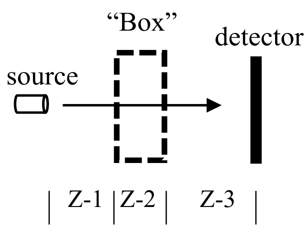



Figure 3.1 Double slit Apparatus with “virtual box”

Let’s divide the model into 3 zones, zone-1 (Z-1) is from source to the slide, which is the left boundary of the Virtual Box; the virtual box is zone-2 (Z-2); zone-3 (Z-3) is from the right boundary of the virtual box to the detector. In Section 3, we study, how photons behave in zone-1 and zone-3.

*) Postulate-1: in zone-1, photons behave as particles.

*) Postulate-2: in zone-3, photons behave as particles.

Postulate-2 predicts that in zone-3, each fringe is formed independently and can be formed partially. Indeed, the experimental results of testing the prediction strongly support postulate-2.

Postulate-1 have been confirmed experimentally in Section 2.4.

There are multi-experiments testing postulate-2 from different perspectives.

## 3.2. Experiments Testing Postulate-2 with Shield Near Detector

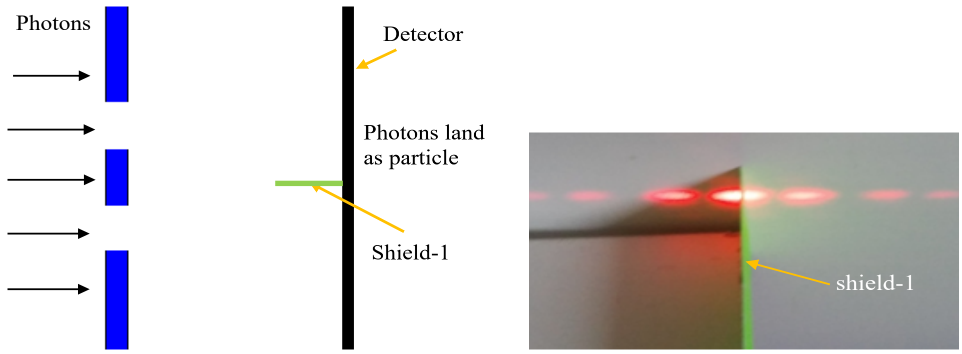
Experiment-3.1 (Figure 3.2): testing postulate-2 with a Shield

Experimental Apparatus: Placing a “shield” (green colored) made of carboard in Z-3 of the regular double slit experiment near the detector. The purpose is to test whether the shield would separate waves and thus, prevent photons from interfering if photons would behave as waves in Z-3. For simplicity, shield-1’s orientation is from the center of the double slit points to the center of the zeroth-order-fringe. We refer shield-1 as longitudinal. Shield-1 is 28 inches long, 1.5 inch wide, and 0.3 mm thick. The distance between the double slit and the detector is 200 inches.

An analogy is a breakwater that break water waves.

The experiment is performed in two setups.

Experimental setup-1 (Figure 3.2a): Shield-1 contacts the detector.

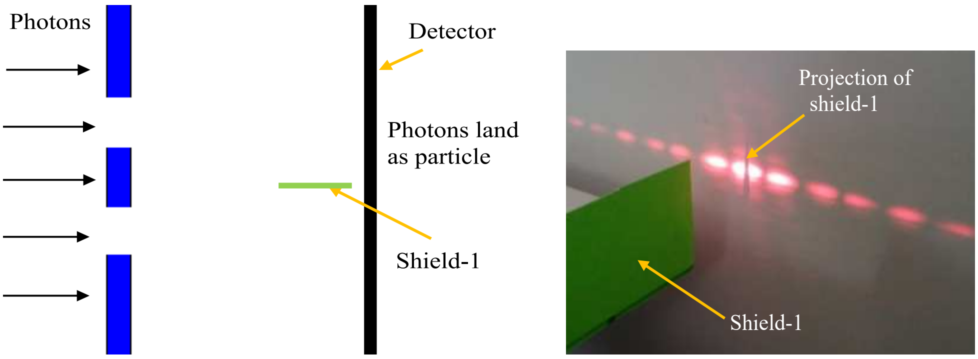



.(a) (b)

Figure 3.2 Testing Postulate-2 with Single Shield (1)

Observation (Figure 3.2b): The interference pattern keeps no noticeable change, namely shield-1 does not affect the interference pattern, which would not be expected if photons behave as waves.

Experimental setup-2 (Figure 3.3a): Shield-1 is one inch away from detector.




.(a) (b)

Figure 3.3 Testing Postulate-2 with Single Shield (2)

Observation (Figure 3.3b): (1) Shield-1 does not affect the interference pattern; (2) there is the projection of shield-1 at the middle of the zeroth-order fringe.

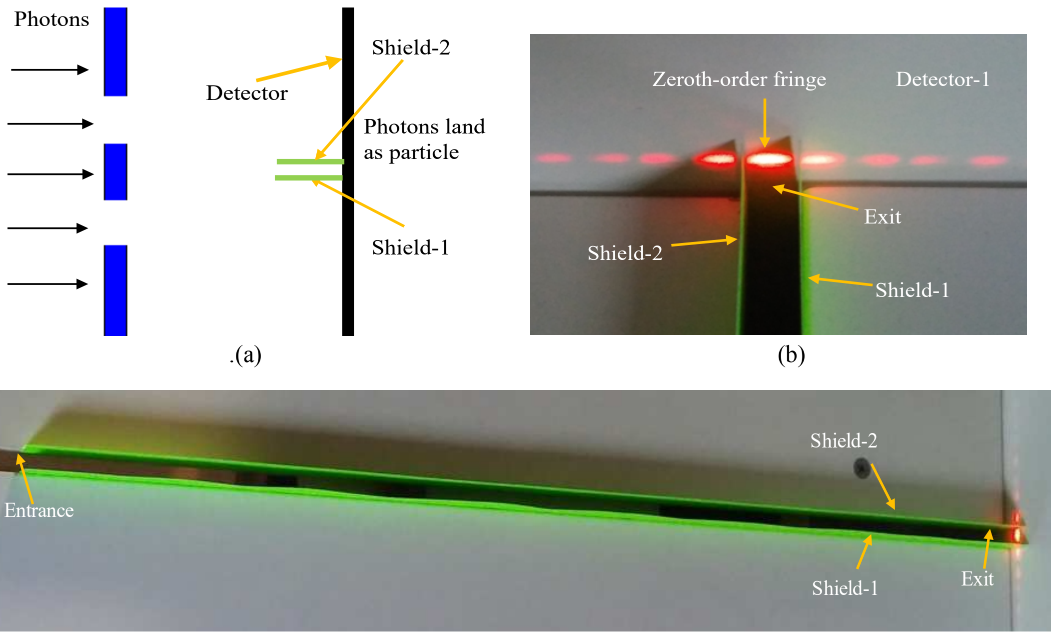
Phenomena of experimt-3.1 would be expected only if photons behave as particles.

Experiment-3.2 (Figure 3.4): Testing Postulate-2 with two Shields (1)

Experimental apparatus: introducing shield-2. Two shields form a narrow channel. The purpose is to test whether the channel would prevent photons from interfering if photons would behave as waves in Z-3. Shield-2 is 28 inches long, 1.5 inch wide, and 0.3 mm thick.

The experiment is carried out in three setups.

Experimental setup-1 (Figure 3.4a): Both shield-1 and shield-2 contact the detector.

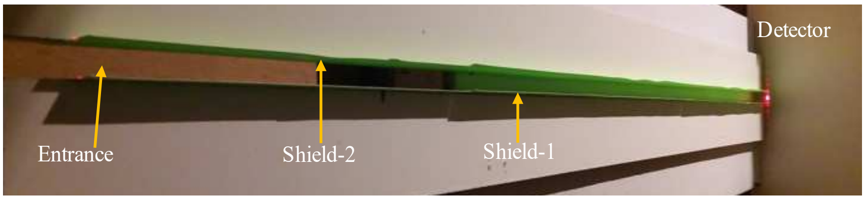



(c)

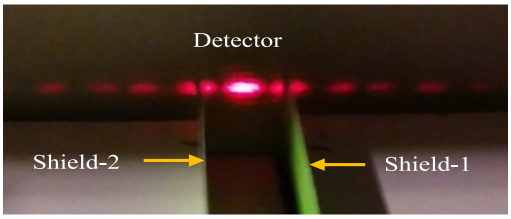
Figure 3.4 Testing Postulate-2 with Two Shields

Observation (Figure 3.4b): We observe the interference pattern that is the same as that there were no shield-1 and shield-2. The existence of two approximately parallel shields of 28 inches long has no effect on the “interference” pattern of 650 nm light, which indicates that photons do not behave as waves near detector.

Experimental setup-2 (Figure 3.5a): Picture of two shields 70 inches long contact to the detector. Note that the picture was shot from the “Entrance” to the detector so that the interference pattern and apparatus show on the same picture and thus, Entrance looks wider.




(a)

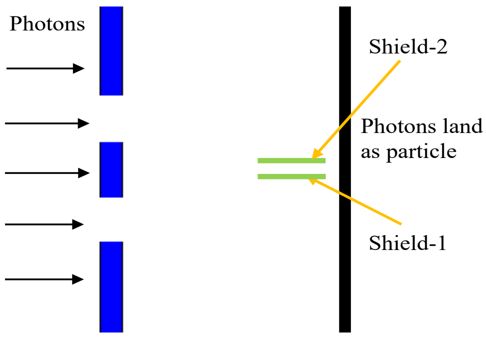



(b)

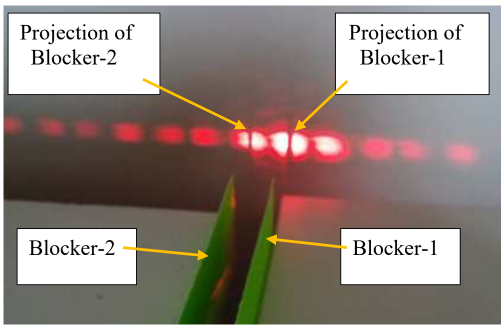
Figure 3.5 Testing Postulate-2 with Two Shields of 70 inches long

Observation (Figure 3.5b): the interference pattern is the same as if there were no shield-1 and shield-2. The existence of two long shields has no effect on the interference pattern. Two projections show at the m = + 1 and m = -1 fringes. Observations indicate that photons behave as particles.

Experimental setup-3 (Figure 3.6a): Moving shield-1 and Shield-2 one inch away from the detector.




(a)



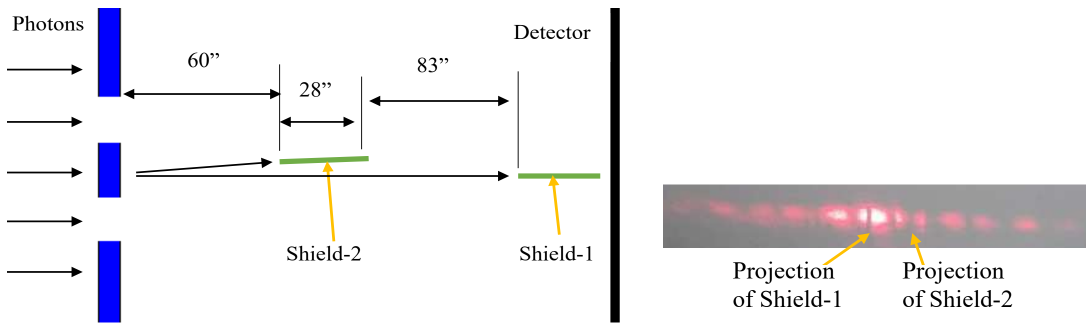

(b)

Figure 3.6 Testing Postulate-2 with Two Shields

Observation (Figure 3.6b): the interference pattern has no change. The projection of shield-1 appears at the middle of the zeroth-order fringe, while the projection of shield-2 appears at the middle of the first-order fringe. Only photons behaving as particles can: (1) pass through the narrow channel; (2) strike at the positions of the zeroth-order fringe and a first-order fringe on the detector; (3) form two projections, while (4) do not disturb the existing interference pattern.

Experiment-3.3 (Figure 3.7): Testing Postulate-2 with two Shields (2)

Experimental setup (Figure 3.7a): Move shield-2 to 60 inches from double slit; shield-1 stays.




. (a) (b)

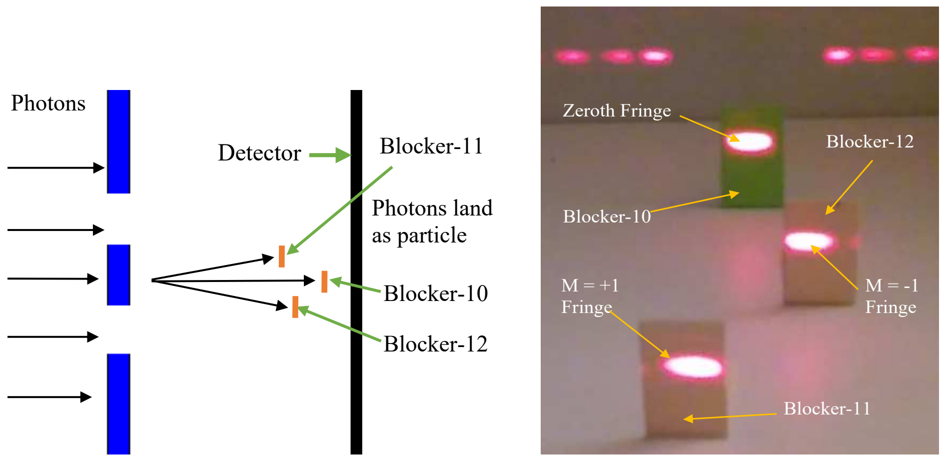
Figure 3.7 Testing Postulate-2 with Two Shields (2)

Observation (Figure 3.7b): The interference pattern has no change. The projection of shield-2 is wider than that of shield-1, since it is closer to the double slit.

Conclusion: Postulate-2 is experimentally confirmed. Only particles can pass through the long and narrow channel between shield-1 and shield-2, and form fringes on the detector; so, photons behave as particles long before landing on the detector. Also, photons are distributed with a wave-like interference pattern on the detector. The phenomena “wave-particle coexistence” would lead to a deeper understanding. Comprehensive-double slit experiments have been carried out at different positions, for example, 40 inches, 80 inches, and 120 inches away from the detector. We always observe the interference pattern and projections of shield-1 and shield-2.

3.3. Experiments Testing Postulate-2 with Blockers Near Detector

Experiment-3.4: Testing Postulate-2 with Blocker. Let us consider five experimental setups. Experimental Setup-1 (Figure 3.8a): blocker-10, blocker-11 and blocker-12, each is 0.5-inch wide, are placed along the normal vector of detector, and separated by 4 inches.

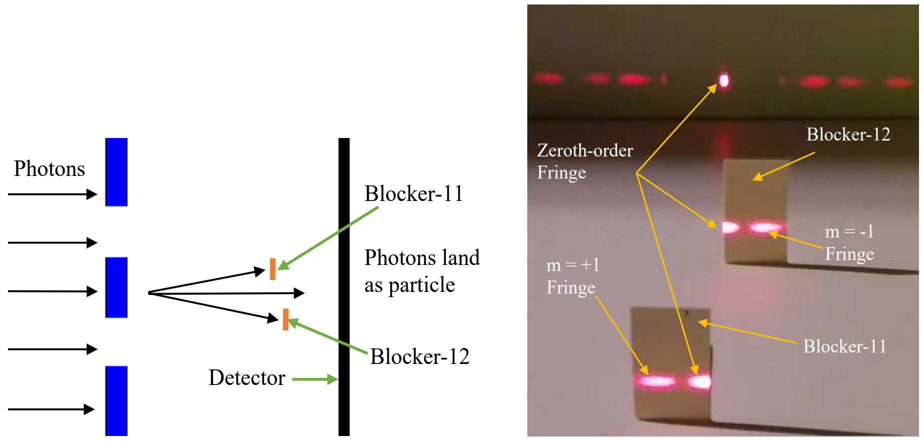



. (a) (b)

Figure 3.8 Fringes Formed Independently (1)

Observation (Figure 3.8b): Three blockers are arranged such that the zeroth-order fringe and two first-order fringes are formed on blocker-10, blocker-11 and blocker-12 respectively. The existence of each blocker does not affect the fringes formed on other blockers and on the detector. Namely, fringes are formed independently.

Experimental Setup-2 (Figure 3.9a): blocker-11 and blocker-12 are placed along the normal vector of the surface of the detector, and separated by 4 inches.




. (a) (b)

Figure 3.9 Fringes Formed Independently and Partially (2)

Observation (Figure 3.9b): Two blockers are arranged such that portions of the zeroth-order fringe are formed on the detector, blocker-11 and blocker-12 respectively. Thus, the fringe can be formed partially. The existence of each blocker does not affect the fringes formed on other blockers and on the detector. Namely, fringes are formed independently.

Experimental Setup-3 (Figure 3.10): blocker-11 and blocker-12 are placed along the normal vector of the surface of the detector.

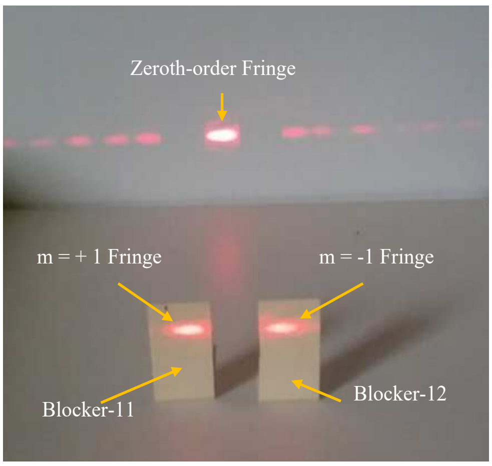



Figure 3.10 Fringes Formed Independently (3)

Observation: The zeroth-order fringe, m = +1 fringe and m = -1 fringe are formed on the detector, blocker-11 and blocker-12 respectively.

Experimental Setup-4 (Figure 3.11): blocker-11 and blocker-12 are placed along the normal vector of the surface of detector, and separated by 4 inches.

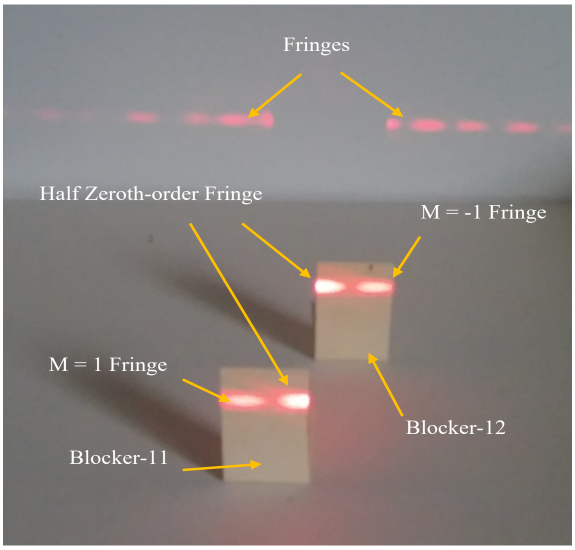



Figure 3.11 Fringes Formed Independently and partially (4)

Observation (Figure 3.11): Portions of the zeroth-order-fringe are formed on blocker-11 and blocker-12 respectively, which indicates that the fringe can be partially formed. The m = +1 fringe and m = -1 fringe are formed on blocker-11 and blocker-12 respectively, i.e., formed independently.

Experimental Setup-5 (Figure 3.12): blocker-11 and blocker-12 are placed along the normal vector of the surface of detector, and separated by 4 inches.

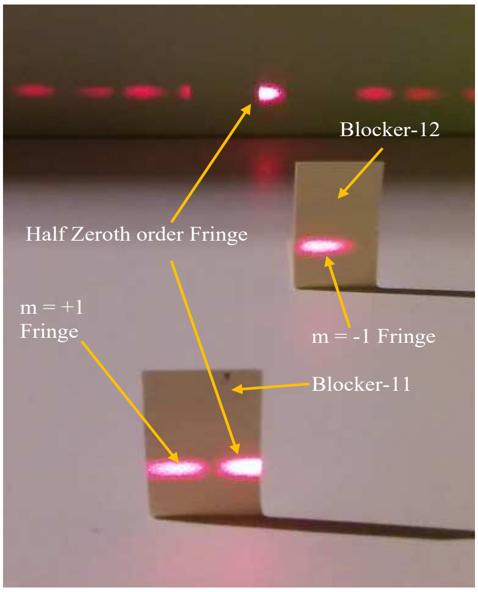



Figure 3.12 Fringes Formed Independently and partially (5)

Observation (Figure 3.12): Portions of the zeroth-order fringe are formed on detector and blocker-11 respectively, which indicates that the fringe can be formed partially. The m = +1 fringe and m = -1 fringe are formed on blocker-11 and blocker-12, respectively, i.e., formed independently.

Conclusion: Fringes are formed independently and partially, which would be expected only if photons behave as particles in Z-3 near the detector.

Postulate-2 is experimentally confirmed.

Some of photons form fringes on blockers, meanwhile, some of photons are distributed like partial of a wave interference pattern on the detector.

3.4. Experiments Testing Trajectory Theory by Blocking Half of Interference Patterns

The purpose of the experiments below is to test the behaviors of light/photons in Z-3 near the detector. In the following experiments, the blocker is 128 inches away from the diaphragm of double slit. To avoid losing generality, we perform experiments with a cross-double slit [16]. First, let us show the interference pattern of a cross-double slit experiment (Figure 3.13) without a blocker.

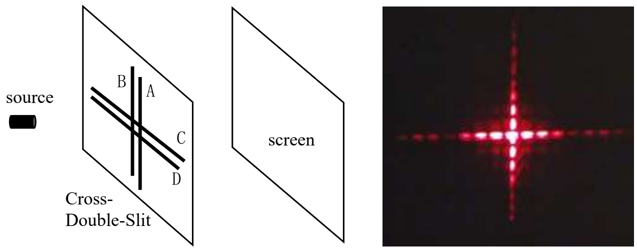
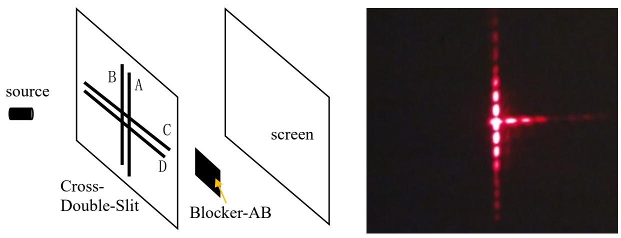



Figure 3.13 Cross double slit experiment

Experiment-3.5 (Figure 3.14): Place blocker-AB and/or blocker-CD to block the different portions of the interference pattern created by double slit AB and double slit-CD. The experiment is performed in three setups.

Experimental setup-1 (Figure 3.14a)**:** Placing blocker-AB such that it blocks the left half of the interference pattern, except the zeroth order fringe.

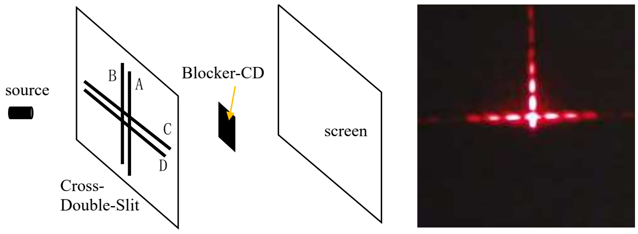



. (a) (b)

Figure 3.14 Block left half of the interference pattern of double slit-AB

Observation (Figure 3.14b)**:** the left half of the fringes are blocked. The positions of the right-half fringes of the interference pattern are not affected by the blocker. The positions of the fringes in the vertical interference pattern are not affected. This is consistent with the statement that the photons move along trajectories.

Experimental setup-2 (Figure 3.15a)**:** Placing blocker-CD, such that it blocks the bottom half of the interference pattern created by double slit-CD.

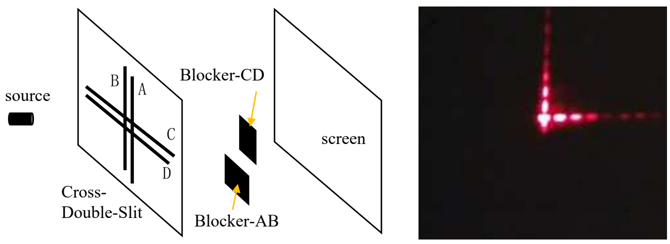



(a) (b)

Figure 3.15 Block bottom half of the interference pattern of double slit-CD

Observation (Figure 3.15b) the bottom half fringes are blocked. The remaining fringes are not affected by blocking, which shows that photons move along trajectories.

Experimental setup-3 (Figure 3.16a)**:** Placing both blocker-AB and blocker-CD to block the different portions of the 1D interference patterns created by double slit-AB and double slit-CD, respectively.

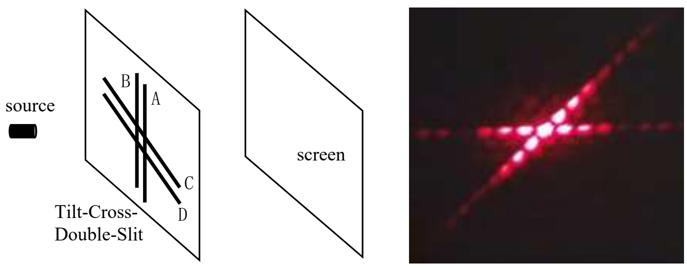



(a) (b)

Figure 3.16 Blocking half of interference patterns created by both double slit-AB and double slit-CD

Observation (Figure 3.16): (A) the bottom half fringes created by double slit-CD are blocked; and (B) the left-half fringes created by double slit-AB are blocked. The remaining fringes are not affected by the existence of the blockers, which shows that photons move along trajectories.

The tilt-cross-double slit apparatus is employed, which consists of a vertical double slit-AB and a tilt-double slit-CD crossing to each other. Figure 3.17 shows the pattern without blocker.

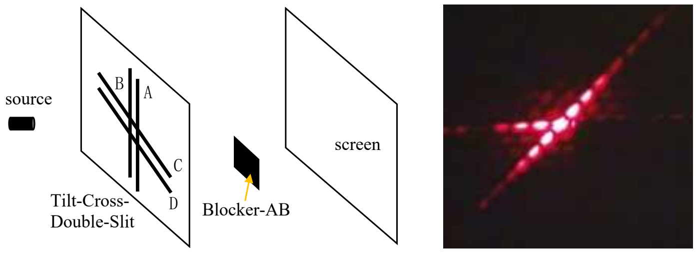



(a) (b)

Figure 3.17 Tilt cross double slit experiment

Experiment-3.6 (Figure 3.18): Tilt-cross-double slit experiments. The blocker-AB is placed to block the different portions of the interference pattern created by double slit AB. The experiment is performed in three setups.

Experimental setup-1 (Figure 3.18a)**:** Placing blocker-AB such that it blocks half of the interference pattern created by double slit-AB.

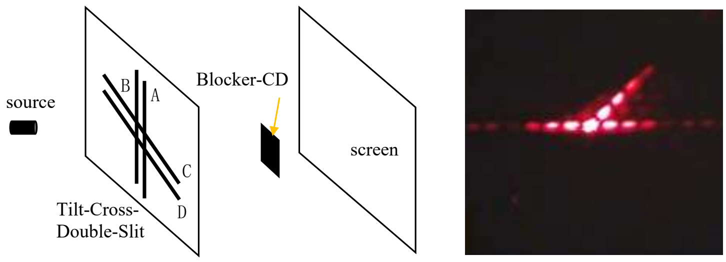



. (a) (b)

Figure 3.18 Tilt cross double slit experiment with blocker-AB

Observation (Figure 3.18b): the horizontal right half fringes are blocked. The remaining fringes are not affected by blocking. The observations show photons move along trajectories.

Experimental setup-2 (Figure 3.19a)**:** Placing blocker-CD such that it blocks the bottom half of the interference pattern created by double slit-CD.

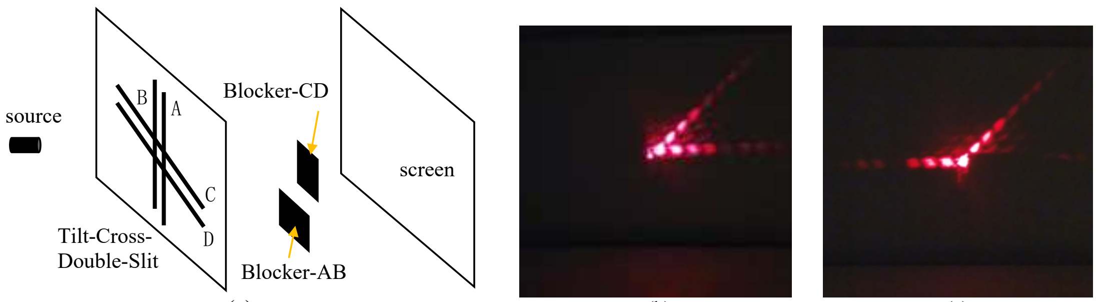



. (a) (b)

Figure 3.19 Tilt cross double slit experiment with blocker-CD

Observation (Figure 3.19b): the tilt bottom half fringes are blocked. The remaining fringes are not affected by blocking.

Experimental setup-3 (Figure 3.20a)**:** Placing blocker-AB and blocker-CD such that half of the interference pattern created by double slit-AB is blocker, simultaneously, half of the interference pattern created by double slit-CD is blocked.




(a) (b) (c)

Figure 3.20 Tilt cross double slit experiment with blocker-AB and blocker-CD

Observation: Figure 3.20b shows that the horizontal left half fringes are blocked, while the tilt bottom half fringes are blocked. The remaining fringes are not affected by blocking. Figure 3.20c shows that the horizontal right half fringes are blocked, while the tilt bottom half fringes are blocked. The rest fringes are not affected by blocking. The observations show that photons move along trajectories.

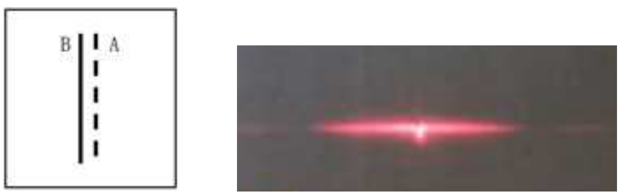
Note that all experiments in Section 3.3 are observed by the naked-eye, and there are no noticeable changes in the brightness of fringes. We cannot determine whether the trajectories cross.

We have shown that the 2D interference patterns are created independently and partially; and that, in Zone-3, photons move along trajectories and behave as particles.

## 3.5. Which Way Cross Double Slit Experiments with Blocker(s)

The which way double slit experiments show that the motion of the particles/photons depends on whether both slits are open, and would be different if one slit was closed. With only one slit open, the distribution of the photons on the screen would create a different pattern that shows the particle nature, according to the practical definition of wave/particle. Bohm's theory has the same statement [22].

The observation of the regular which way double slit experiment is shown in Figure 3.21, where an "observer" is set behind slit A (denoted by dashed slit A).




(a) (b)

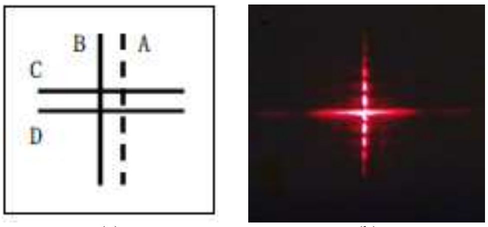
Figure 3.21 Regular which way double slit experiment

Figure 3.22 shows that the half of the pattern of Figure 3.21b is blocked.

Figure 3.22 Which way double slit experiment: blocking half pattern

For the Young's double slit experiment, if the trajectory theory holds, e.g., trajectories do not cross, one knows which way a photon passing through without observing and destroying the interference pattern.

A which way 2D cross double slit experiment was performed (Figure 3.23).




. (a) (b)

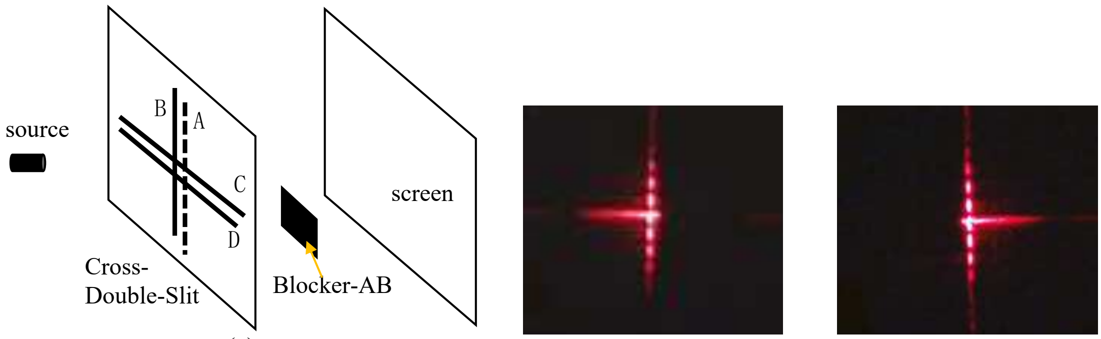
Figure 3.23 Which way 2D cross double slit experiment

By the same argument that the which way 1D double slit experiments support the complementarity principle, the which way 2D cross double slit experiments oppose the Bohr's complementarity principle [21]. Namely, in the same experiment with the same light source, the same diaphragm of the cross double slit and the same detector, light/photons behave as both waves and particles.

Now let us block different portions of the patterns of the "which way experiments".

Experiment-3.7: Which way cross double slit experiments with blocker(s)

Experimental Setup-1 (Figure 3.24a)**:** Place blocker-AB at different positions.

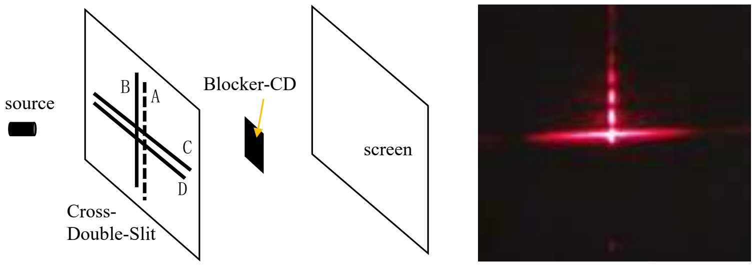



(a) . (b) (c)

Figure 3.24 Which way 2D cross double slit experiments with blocker-AB

Observations: Figure 3.24b shows that block-AB blocks the right half of the pattern. Figure 3.24c shows that the left half of the pattern created by double slit-AB is blocked. In both setups, the remaining parts of both the pattern and the interference pattern are not affected, which is the consequences of photons propagating along trajectories.

Experimental Setup-2 (Figure 3.25a)**:** Place blocker-CD between the cross double slit and the screen.

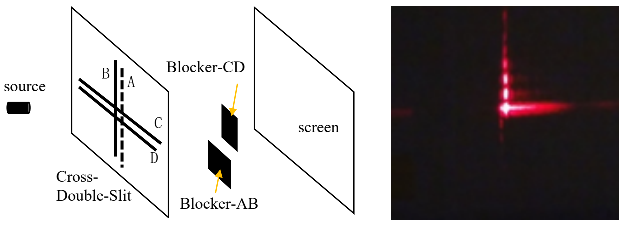



. (a) (b)

Figure 3.25 Which way 2D cross double slit experiments with blocker-CD

Observations: Figure 3.25b shows that block-CD blocks the bottom half of the interference pattern created by the double slit-CD, but it does not affect the top half of the interference pattern. The pattern created by the double slit-AB is not affected.

Experimental Setup-3 (Figure 3.26a)**:** Placing both blocker-AB and blocker-CD between the cross double slit and the screen.



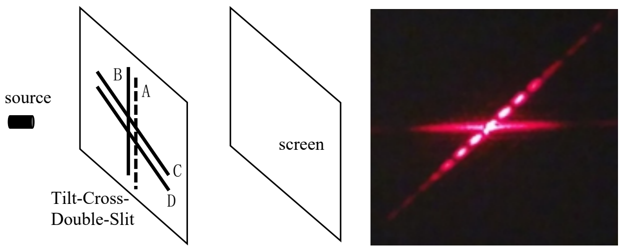

. (a) (b)

Figure 3.26 Which way 2D cross double slit experiments with blocker-AB and blocker-CD

Observations: Figure 3.26b shows that block-CD blocks the bottom half of the interference pattern created by the double slit-CD, but does not affect both the top half of the interference pattern and the right half of the pattern created by the double slit-AB. Block-AB blocks the left-half pattern, but does not affect both the right half of the pattern and the top half of the interference pattern. The phenomena are the consequences of photons propagating along trajectories.

Which way 2D tilt cross double slit experiments have been performed (Figure 3.27).

Next let us perform the which way tilt cross double slit experiments with blocker(s).




. (a) (b)

Figure 3.27 Which way tilt cross double slit experiments

Experiment-8: Which way 2D tilt cross double slit experiments with blocker(s). The experiment is performed in three setups.

Experimental Setup-1 (Figure 3.28a)**:** Placing blocker-AB between the tilt cross double slit and the screen.

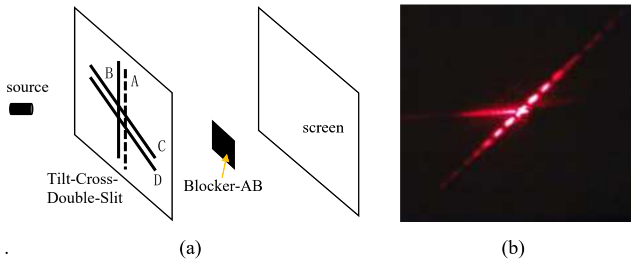



Figure 3.28 Which way tilt cross double slit experiment with blocker-AB

Observations: Figure 3.28b shows that block-AB blocks the left half of the pattern created by the double slit-AB with "observation at slit A", while it does not affect both the right half of the pattern and the interference pattern created by the double slit-CD.

Experimental Setup-2 (Figure 3.29a)**:** Placing blocker-CD between the tilt cross double slit and the screen.

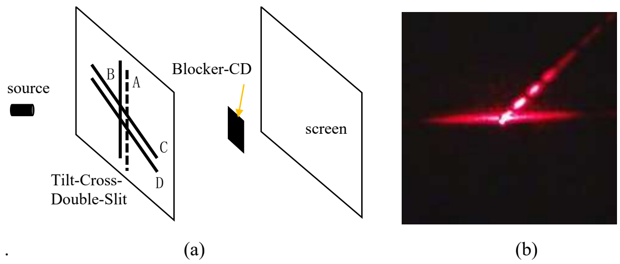



Figure 3.29 Which way tilt cross double slit experiment with blocker-CD

Observations: Figure 3.29b shows that block-CD blocks the bottom half of the interference pattern created by the tilt double slit-CD, while it does not affect both the top half of the interference pattern and the pattern created by the double slit-AB.

Experimental Setup-3 (Figure 3.30a)**:** Place both blocker-AB and blocker-CD between the tilt cross double slit and the screen.

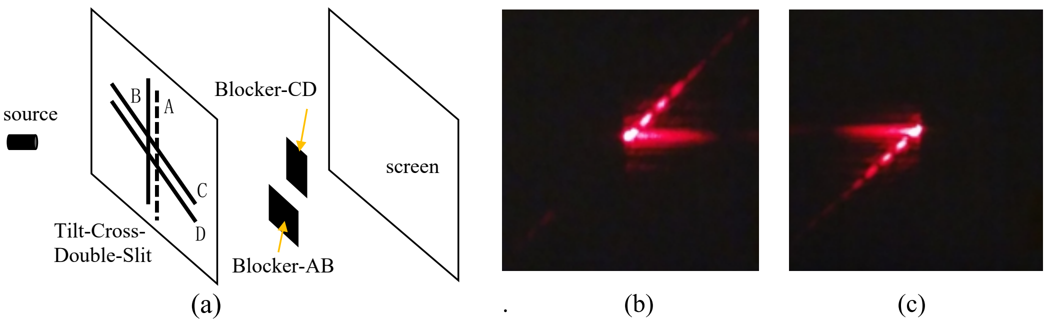



Figure 3.30 Which way tilt cross double slit experiment with blocker-AB and blocker-CD

Observations: Figure 3.30b shows that block-CD blocks the bottom half of the interference pattern created by the tilt double slit-CD, but it does not affect both the top half of the interference pattern and the right half of the pattern created by the double slit-AB. Block-AB blocks the left half of the pattern created by the double slit-AB with "observation at slit A", but it does not affect both the right half of the pattern and the top half of the interference pattern created by the tilt double slit-CD.

Figure 3.30c shows that block-CD blocks the top half of the interference pattern created by the tilt double slit-CD, but it does not affect both the bottom half of the interference pattern and the left half of the pattern created by the double slit-AB. Block-AB blocks the right half of the pattern created by the double slit-AB, but it does not affect both the left half of the pattern and the bottom half of the interference pattern created by the tilt double slit-CD.

Although each photon travels along its own trajectory, it is challenge for the trajectory theory to interpret the which way 2D cross double slit experiments described in Section 3.5.

### 3.6. Experiments Testing Postulate-2 with Shields and Blocker.

We have shown that, on the one hand, longitudinal shield(s) do not disturb the interference pattern in zone-3. On the other hand, blockers do block the propagation of photons as photons are particles. Now let's show the effects of combinations of shields and blockers.

Experiment-3.9 (Figure 3.31): Testing Postulation-2 with Shield and Blocker. The experiment is performed in three setups.

Experimental setup-1 (Figure 3.31a): Shield is one inch away from detector. Blocker is positioned next to shield.

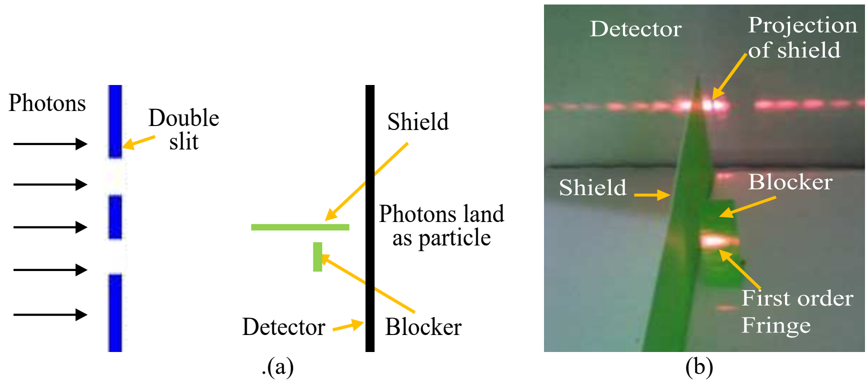



Figure 3.31 Testing Postulate-2 with Shield and Blocker (1)

Observation (Figure 3.31b): (1) Shield does not affect the interference pattern at all; (2) there is the projection of the shield at the middle of the zeroth-order fringe; (3) blocker is so arranged that it does block a first-order fringe.

Experimental setup-2 (Figure 3.32a): Shield is one inch away from detector. Blocker-1 and blocker-2 are placed on both sides of shield respectively.

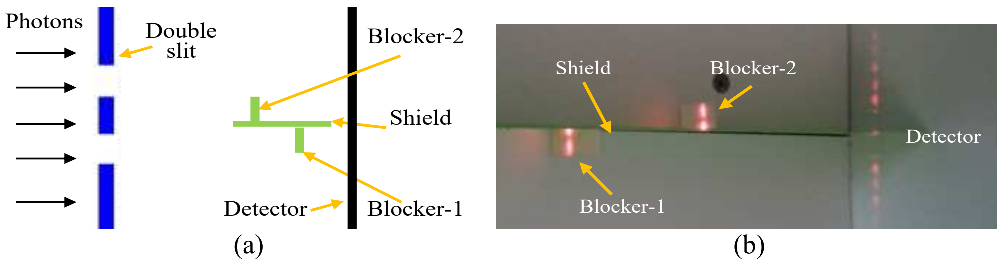



Figure 3.32 Testing Postulate-2 with Shield and Blocker (2)

Experimental setup-3 (Figure 3.33a)

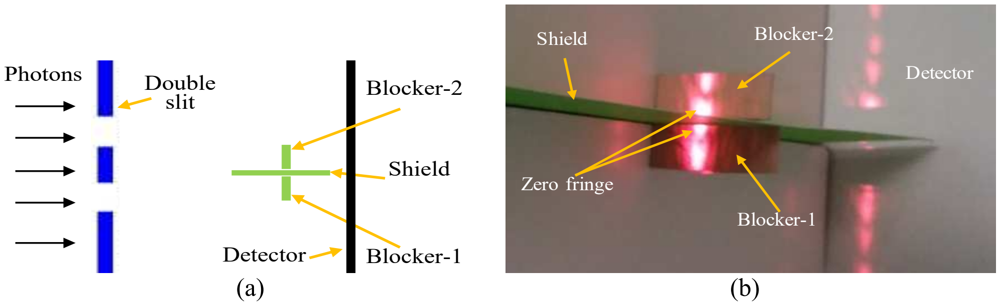



Figure 3.33 Testing Postulate-2 with Shield and Blockers (3)

Observation (Figure 3.32b and 3.33b): Blocker-1 and Blocker-2 are so arranged that the zeroth-order fringe is formed on both blocker-1 and blocker-2 respectively. Two first-order fringes are formed on blocker-1 and blocker-2, next to the half of the zeroth-order fringe, respectively. Shield can divide the zeroth-order fringe into two parts, but cannot disturb the remaining fringes, which indeed indicates that photons behave as particle before landing on detector

Experiment-3.10: Testing Postulation-2 with Shields and blocker.We perform this experiment in three setups.

Experimental Setup-1 (Figure 3.34a): place blocker-1 at the other end of shield-1 and shield-2, where we denote it as Entrance (Figure 3.34b).

Observation (Figure 3.34b): The interference pattern is formed on blocker-1 instead of the detector.

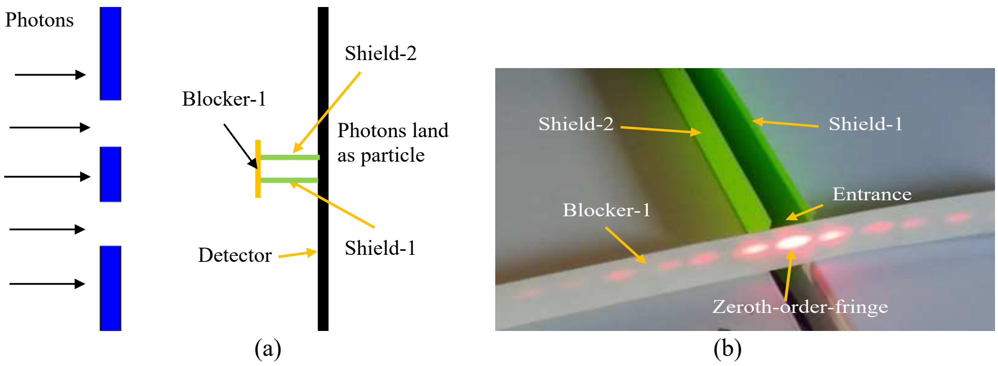
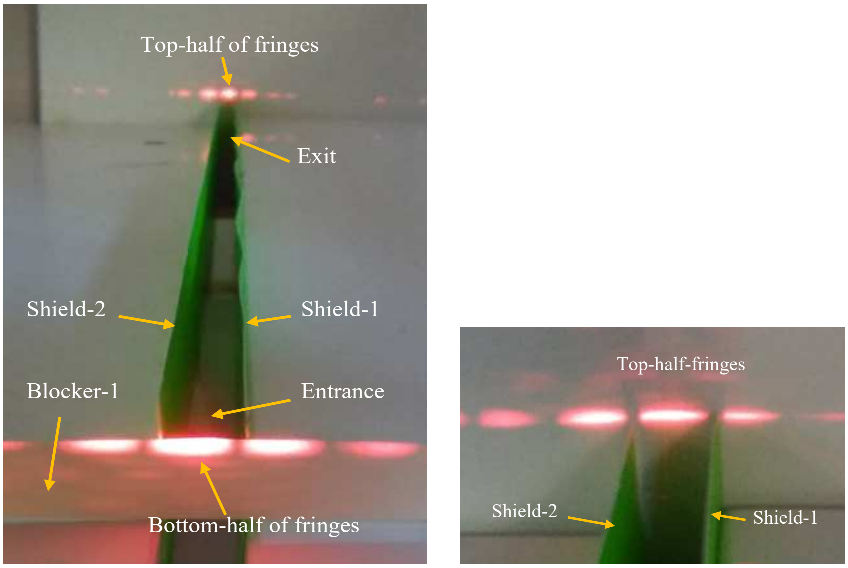


Figure 3.34 Testing Postulate-2 with Shields and Blocker

Experimental Setup-2 (Figure 3.35a): Cutting the top portion of blocker-1.

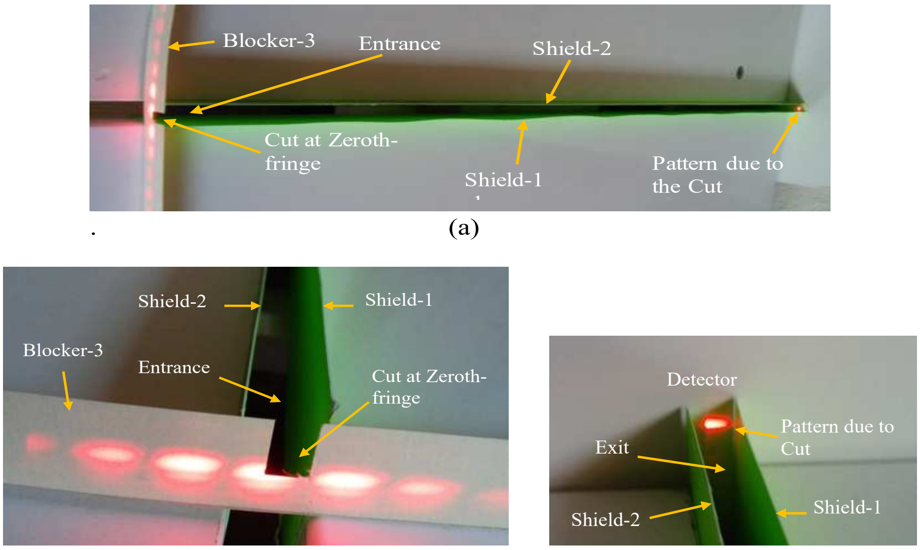



.(a) (b)

Figure 3.35 Testing Postulate-2: Cut Top Half of Blocker-1

Observation (Figure 3.35): the bottom half of the fringes still show on blocker-1, while the top half show on the detector. Namely each fringe can be formed partially. And shields have no effect on the positions of the interference pattern at all.

Experimental Setup-3 (Figure 3.36): cut a "U" shape gap at the position of the zeroth-order fringe on blocker-3.




(a)

(b) (c)

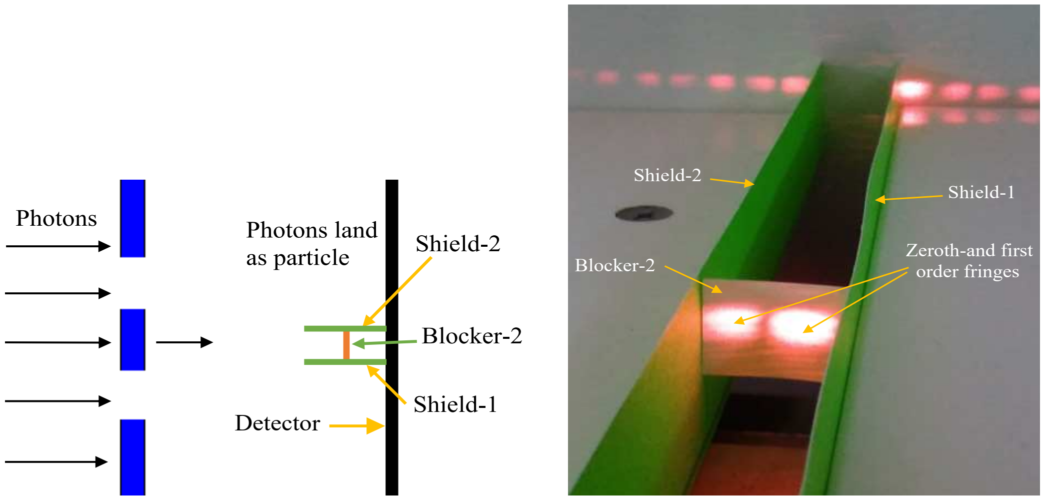
Figure 3.36 Testing Postulate-2: Blocker-3 with Cut

Observation (Figure 3.36b and 3.36c): Photons pass through the cut and form the exactly same shape of patterns on the detector, which shows the particle nature of light and that photons move along straight lines.

Experiment-3.11: Testing Postulate-2 with Shields and Blocker.

We perform this experiment in two setups.

Experiment Setup-1 (Figure 3.37a): insert transverse blocker-2 one inch wide into the channel formed by shield-1 and shield-2.




. (a) (b)

Figure 3.37 Blocker-2 in Channel (1)

Observation (Figure 3.37b): Two fringes are formed on blocker-2, and the remaining fringes are formed on the detector. Namely, Fringes can be formed independently. Two shields have no effect on the interference pattern. This observation indicates that photons behave as particles.

Experimental Setup-2 (Figure 3.38): cut two triangles on blocker-2 at the locations of the zeroth-order fringe and a first-order fringe respectively. Then place blocker-2 into the channel.

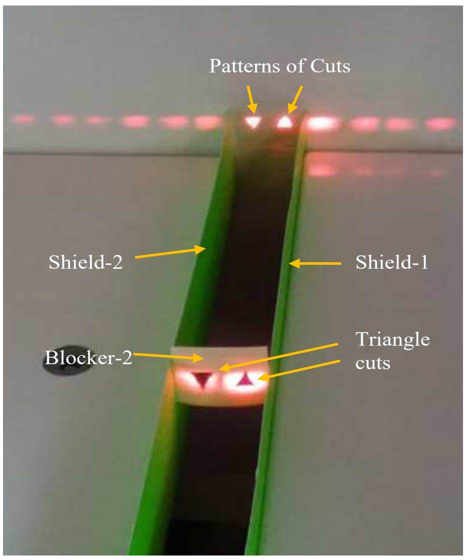


Figure 3.38 Blocker-2 with Two Cuts (2)

Observation (Figure 3.38): Photons pass through two triangle-shaped cuts and form exactly the same triangle-shaped patterns on the detector, which shows the particle nature of photons, namely photons move along straight lines. Note that photons are not directly from the source; they are just pass through a double slit and were supposed to behave as waves. The conclusion is that photons behave as particles.

Postulate-2 is confirmed experimentally.

Meanwhile, some of photons are distributed like a partial wave interference pattern on the detector.

### 3.7. Testing Postulate-2 with 2D-cross-double slit

Without losing generality, we perform comprehensive double slit experiments with two cross-double slit that consist of five and six double slits crossing at the same spot. Each of double slit creates an interreference pattern independently.

Experiment-3.12 (figure 3.39): The experiment is performed in four setups.

Experimental Setup-1 (Figure 3.39): parallel shield-1 and shield-2 contact the detector.

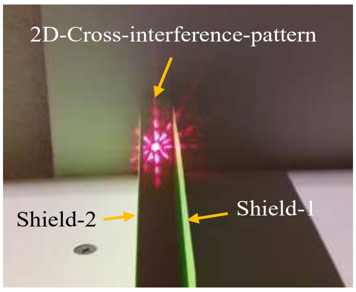
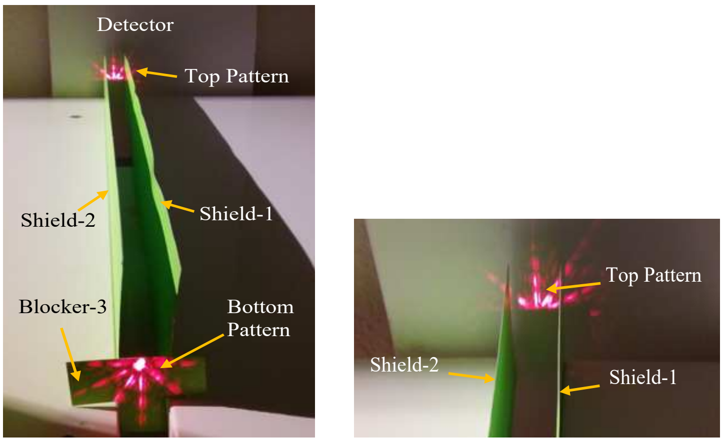



Figure 3.39 2D-pattern vs. Channel (1)

Observation: the channel of two shields does not disturb the 2D-interference pattern.

Experimental setup-2 (Figure 3.40a): using blocker-3 to block the bottom portion of the 2D-interference pattern.




. (a) (b)

Figure 3.40 Testing Postulate-2 with Cross-double slit (2)

Observation (Figure 3.40b): the top portion of the 2D interference pattern is shown on the detector, while the bottom portion is shows on blocker-3.

Experimental setup-3 (Figure 3.41): using blocker-3 to block bottom-right corner of the 2D-interference pattern.

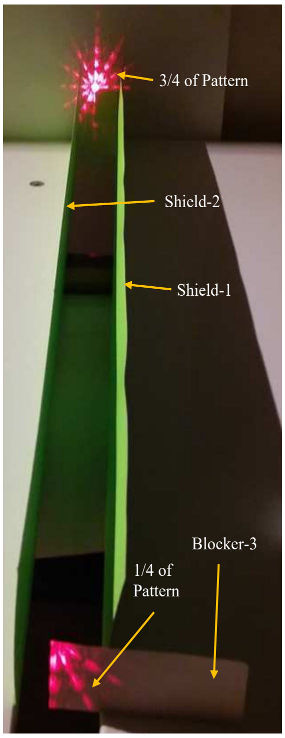



Figure 3.41

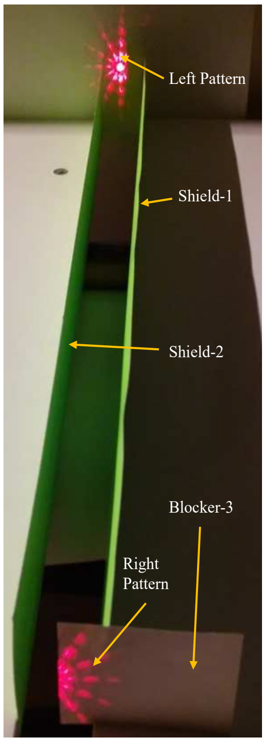



Figure 3.42

Observation (Figure 3.41): the ¾ portion of the 2D interference pattern shown on the detector, while the bottom-right portion of the interference pattern shows on blocker-3.

Experimental setup-4 (Figure 3.42): using blocker-3 to block right portion of the 2D-interference pattern.

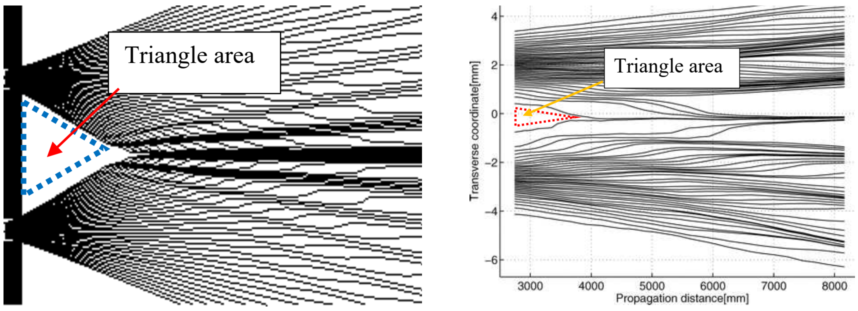
Observation (Figure 3.42): the left portion of the 2D interference pattern shows on the detector, while the right portion of the interference pattern shows on blocker-3.

Conclusion: 2D patterns are created independently and partially. Only particle can behave in such way. Postulate-2 is confirmed experimentally: in zone-3, photons move along predetermined trajectories to form fringes and thus, behave as particles.

It is a challenge to consistently interpret the experiments in Section 3.

## 4. Experimental Test of Trajectory Theory: Contact/Near Diaphragm of Double Slit

de Broglie and Bohm theory [23] [24] [25] states that photons propagate along trajectories. One prediction of computer simulations of de Broglie-Bohm theory is that the possible trajectories for particle (Figure 4.1a, extracted from reference [26]) [27] [28] and for photons (Figure 4.1b, extracted from reference [29]) cannot cross. We notice an implicit prediction that there is a triangle-shaped area behind the double slit, in which there is no trajectory (Figure 4.1a and 4.1b), namely, no particle/photons pass through this area (hereafter referred both as “predictions”).




. (a) (b)

Figure 4.1 Computer simulations of trajectory interpretation of double slit experiments

To our knowledge, no experiment has either been performed or proposed to test these two predictions.

In this Section, we perform more comprehensive double slit experiments that test above mentioned two predictions of computer simulations of de Broglie-Bohm trajectory theory in Z-2.

**4.1.** Experiments Testing Trajectory Theory: Shield Contacting Diaphragm of Double Slit

We observed that the height of the triangle is longer than the spacing between two slits. Thus, we test whether there are photons in the triangular area using shield (Figure 4.2).

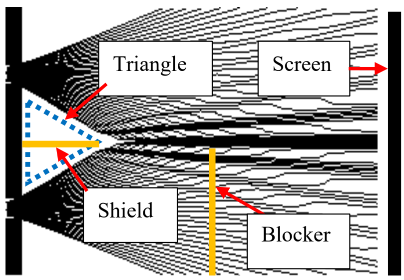


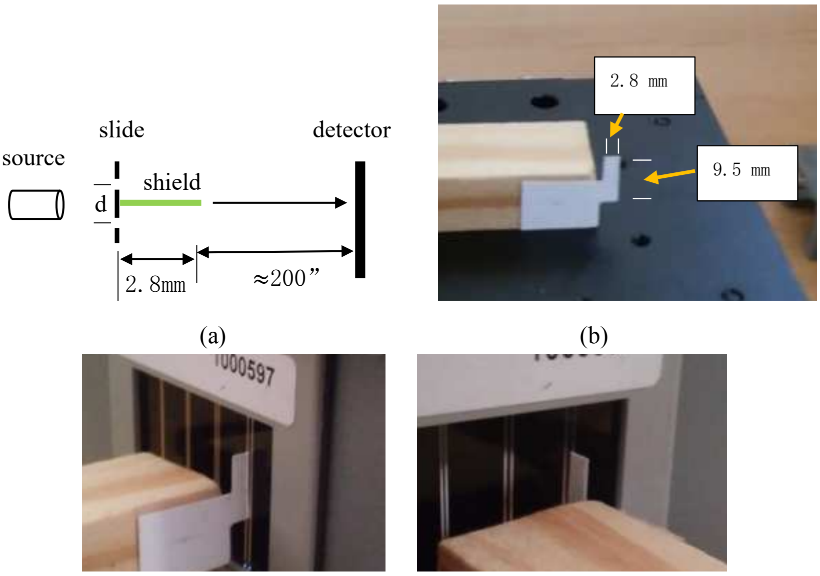

Figure 4.2 Outline of experiments

Note that in Figure 4.2, we use Figure 4.1a for a schematic drawing of photon experiments instead of Figure 4.1b for photons because it is clearer. The conclusions are the same.

We perform two experiments to test whether there are photons in the triangular area.

Experiment-4.1 (Figure 4.3): we show that, with a narrow shield, the trajectories cross, while the interference pattern exists.

Experimental Setup: making a shield (gray colored) and gluing it to an object (Figure 4.3b). The shield is 2.8 mm long, 9.5 mm wide, and 0.12 mm thick. Note that the drawing is not to scale.




(a) (b)

(c) (d)

Figure 4.3 Experimental setup

Place the shield along the virtual centerline and contacting the double slit at the position between two slits, where the spacing “d” between two slits is 1 mm (Figure 4.3a). Figure 4.3c is the picture taken from the right side of the shield, and Figure 4.3d is the picture taken from the left side.

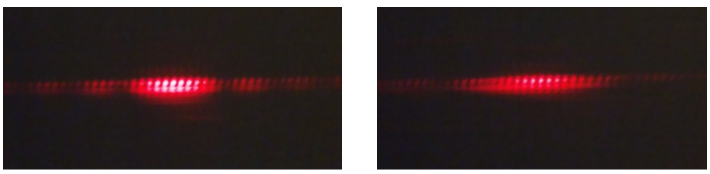
Note that the “contact” is macroscopic “contact”, namely there are actually “gaps” between the shield and the double slit. More precise apparatus is designed in Appendix.

Then turning on the laser.

Observation: the light from the right-side slit shins on the right side of the shield (Figure 4.4a), while the light from the left-side slit shins on the left side of the shield (Figure 4.4b). The light spots on both sides of the shield indicate that there are light/photons in the triangle area.

(a) (b)

Figure 4.4 Experiments with Shield Contacting Double Slit



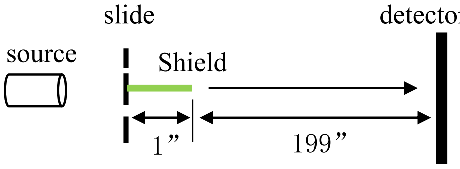
(a) (b)

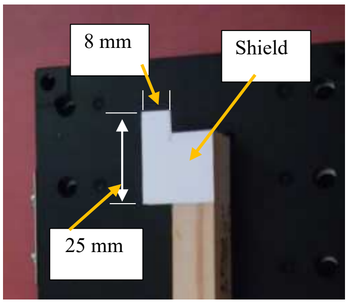
Figure 4.5 Regular interference pattern vs. interference pattern of double slit with shield

Figure 4.5a shows the interference pattern of the double slit without the shield. Figure 4.5b is the interference pattern of the same double slit with the shield.

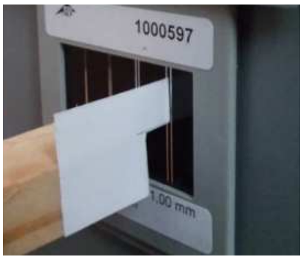
Experiment-4.2: with a wider shield, the trajectories cross and the interference pattern exists.

Experimental Setup (Figure 4.6): making an “L”-shaped shield (grey colored) and gluing it to an object (Figure 4.6b). The shield is 25 mm (one inch) long, 8 mm wide, and 0.12 mm thick.




. (a) (b)



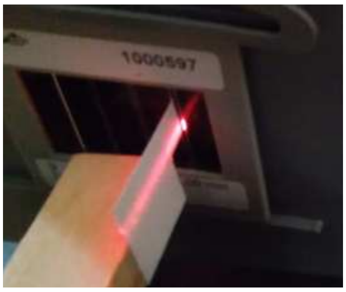


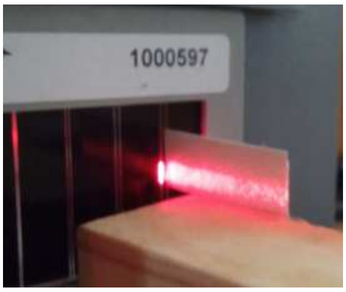
.(c) (d)

Figure 4.6 Schematic and Shield

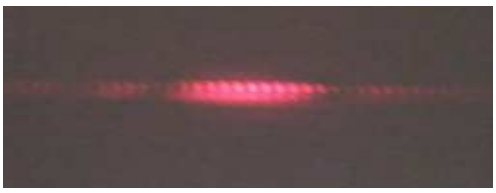
The shield is placed along the virtual centerline and contacts the double slit at the point between two slits (Figure 4.6c and 4.6d), where the spacing “d” between two slits is 1 mm (Figure 4.6).

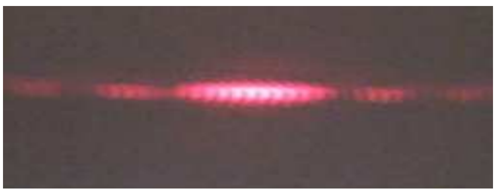
Then turning on the laser.






. (a) (b)





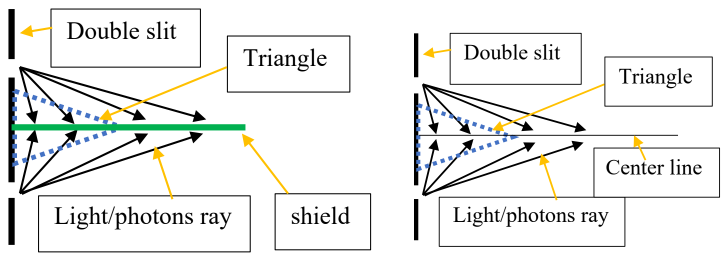
. (c) (d)

Figure 4.7 Experiment with shield contacting double slit

Observation: the light from the right-side slit shins on the right side of the shield (Figure 4.7a), while the light from the left side slit shines on the left side of the shield (Figure 4.7b). The light spots on both sides of the shields indicate that there are light/photons in the triangle area. The shield is brightest close to the slits. The interference pattern exists (Figure 4.7c), but is dimmer. For comparison, Figure 4.7d shows the interference pattern of the same double slit, but without the shield.

Conclusion: in the triangular area, first there are light/photons; second trajectories cross. Thus, we suggest that the experimental observations challenge either the predictions of computer simulation or the trajectory theory.

It is reasonable to assume that, without the shield (Figure 4.8b), the behavior of light/photons in and near the triangular area would be the same as that with the shield (Figure 4.8a).



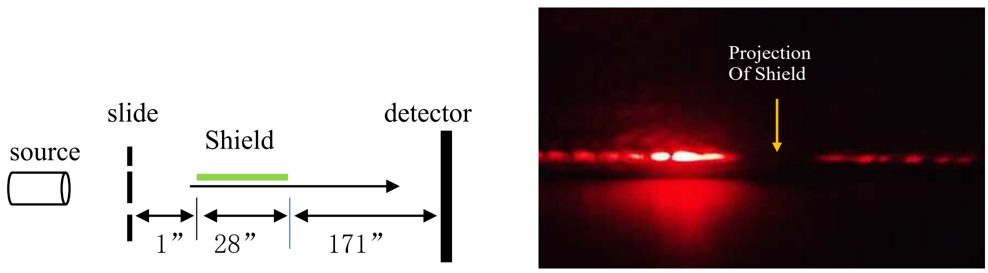

.(a) (b)

Figure 4.8 Schematics of Experiment

4.2. Experiments Testing Trajectory Theory: Shield/Blocker Placed Near Diaphragm of Double Slit

Experiment-4.3:

Experimental Setup (Figure 4.9a): the shield of 28 inches long is placed at a position 25 mm from the double slit. The spacing between two slits is 0.25 mm.




.(a) (b)

Figure 4.9 Schematic Setup and Observation

Observation (Figure 4.9b): both the “interference” pattern and the projection of the shield show on the detector. The particle nature still shows. Thus, the width of zone-3 is at least 199 inches, in which photons behave as particles. Note that the distance between the slide and the detector is 200 inches.

Now let’s calculate the width of the projection of the shield on the detector. The regular equation holds,

$y = \frac{\lambda L}{d} m$.                (1)

For experiment-4.3, the wavelength is 650 nm, the distance from the double slit to one end of the shield is one inch, the spacing between two slits is 0.25mm, and the cross-section, thickness, of the shield is 0.3 mm. Substituting into Eq. (1), we obtain $m \approx 4.6$, namely up to the 4th bright fringes are all blocked by the cross section of the shield.

Experiment-4.4:

In previous comprehensive double slit experiments, we placed the blocker(s) to block individual fringes. According to Bohm's theory, photons' trajectories from different slits cannot cross, namely, blocking one side of fringes should not affect the fringes formed by photons passing through other slit. We place the blocker to block more, even half, of the fringes simultaneously. The purpose is to test, when we place the blocker to block the portion of the interference pattern, what will happen to the remaining portion of the interference pattern.

Experimental Setup (Figure 4.10): using the regular double slit apparatus. The blocker is placed one inch from the slide. The spacing between two slits is 0.25mm.

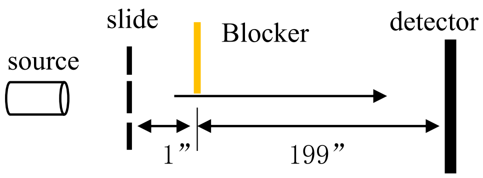



Figure 4.10

The distance between the slide and the detector is 200 inches.

Experimental procedure-1: Before placing the blocker, turning on the laser source, the interference pattern is shown on the detector (Figure 4.11a).

. (a) (b)

Figure 4.11 Interference pattern of double slit experiment

Experimental procedure-2**:** Then, placing the blocker at a position such that (1) it is near the double slit, but the interference pattern still exists, and (2) all of the fringes on the left side of the zeroth-order fringes are blocked.

Observations (Figure 4.11b): We observe the following: (1) The positions of the zeroth-order fringe and the fringes on the right side are not affected, which is consistent with trajectory theory; (2) On the other hand, each remaining fringe becomes dimmer.

According to the Bohm theory, the blocked photons from the left slit would make no contribution to the right-side fringes. The experimental observations show the opposite; and thus, the trajectory theory is challenged. Note that there is a "tail" on the left side of the zeroth-order-fringe, which is due to the diffraction of the edge of the blocker [30].

Conclusion: it is a challenge to consistently interpret the experiments in Section 4.

**Appendix: Novel Diaphragm for Double Slit Experiments**

In preliminary Experiment-4.1 and Experiment-4.2 of Section 4.2, the shields *contact* the diaphragms of the double slit (Figure 4.3 and 4.6). However, the "contact" is a macroscopic-type contact, i.e., actually, there are "gaps" between the shield and the diaphragm of the double slit.

For further double slit experiments, we design new apparatuses to eliminate the gap between the shield and the double slit, they are one piece now (Figure A1) [16].

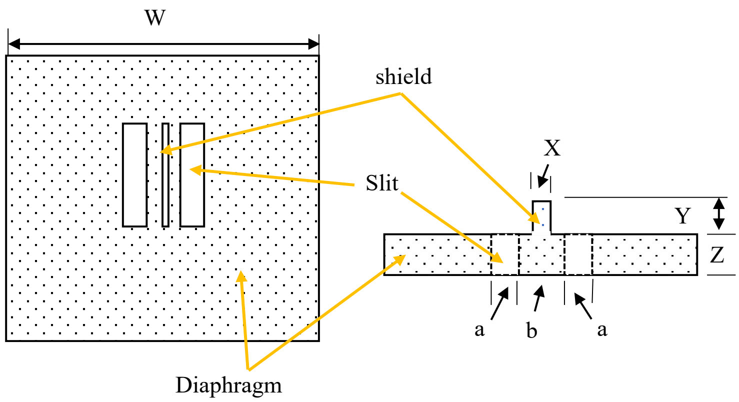



Figure A1 Novel Diaphragm for Double Slit Experiments

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