

# Comprehensive Double Slit Experiments-Exploring Experimentally Mystery of Double Slit

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## Research Article

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# Comprehensive-Double Slit Experiments

## ---Exploring Experimentally Mystery of Double slit

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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 pilot waves. In this article, to study the mystery, we introduce a model, in which a slide of double slit and its neighbourhood is represented as a "virtual box". The model is divided into 3 zones, zone-1 (Z-1) is from source to the slide (left side of the virtual box), the virtual box is zone-2 (Z-2), zone-3 (Z-3) is from the right side of the virtual box to the detector. We propose and carry out: (1) modified-double slit experiments for testing photons' behaviour in Z-1; and (2) comprehensive-double slit experiments for detecting photons' behaviour in Z-3. The latter discovers novel phenomena in Z-3: (1) the fringes of the interference patterns are formed independently and can be formed partially; and (2) the longitudinal shields (up to 180 centimeter long) do not disturb the interference patterns at all. These novel phenomena would not be expected if photons behave as waves in Z-3. We experimentally show: (1) before striking at the slide of a double slit and/or a cross-double slit, i.e., in Z-1, photons emitted by a laser source behave as particles; (2) before striking at the detector, i.e., in Z-3, photons behave as particles; (3) the range of the virtual box is less than 3 centimeter. On the other hand, the interference patterns do exist in the modified-double slit experiments and the comprehensive-double slit experiments. This seems a paradox. We suggest an interpretation to address the paradox. The comprehensive-double slit experiments are new tools for study the double-slit experiments, complementarity principle and wave-particle duality. Progress in studying the mystery of the double slit experiment is presented.

**Keywords:** double slit experiment, quantum mechanics, cross-double slit experiment, complementarity principle, wave-particle duality

### 1. Introduction

The evolution of the concept of light/photons has a long history. In 1801, Young performed a classical double slit experiment, which demonstrated that light could behave as waves and thus, proved the wave theory of light of Huygens (1678). Since then, Descartes (1637)/Newton's (1704) corpuscular/particle theory of light has faded out.

Einstein (1905) proved that light is quanta [1], which, combining with Young's double slit experiment, led to wave-particle duality [2].

Louis de Broglie (1924) [3] postulated that quantum particles behave as wave, which was verified for electrons (Davisson and Germer, 1927) [4].

Bohr (1927) proposed the complementarity principle [5] based on both theory and experiments [6] [7] [8]. Bohr implies that it is impossible that objects in quantum mechanics have intrinsic properties that are independent of measuring device. The objects have certain pairs of complementary properties, such as wave and particle, which cannot all be observed or measured simultaneously in the same experiment.

The standard interpretation of Young's double slit experiment is that the light behaves the same as waves before and after passing through the slide of the double slit. Namely, until strike on a detector, photons behave as waves and interfering. On the other hand, while the interference pattern remains, photons are always found to be absorbed at the discrete points of the detection screen, as individual particles; the interference pattern appears via the varying density of these particles hit on the screen [9]. It is interpreted as that the wave functions exist until are "collapsed" by the detector [10].

Feynman called "[the double slit experiment] contains the only mystery [of quantum mechanics]" [11]. Namely, if we could understand this double slit experiment, we would gain insight into the heart of quantum theory.

The pilot wave of the de Broglie-Bohm theory provides an alternative interpretation [12] [13], by which photons propagate along trajectories.

Moreover, the nature of photon 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?" [14].

We argue that one of the reasons why the mystery of the double slit experiment is long-standing is the lack of rigorous experimental data. Comprehensive double slit experiments are needed to study the phenomenon in detail and to provide more basic facts for theorists to work on.

Recently, to explore this mystery, novel cross-double slit experiments and which-way cross-double slit experiments have been proposed and performed [15] [16] [17]. To interpret the cross-double slit experiments consistently is a challenge.

In this article, we propose comprehensive-double slit experiments to test whether photons behave as waves and interfere to each other before striking at the detector. These novel experiments are based on regular double slit experiments. One of characteristics of those experiments is that the experimental results are visually observable without ambiguity.

## **2. A Model and Outline**

We first review the standard Young's double slit experiments (Figure 1). The apparatus, consisting of a laser source (not shown), a slide of double slit and a detector/screen, is utilized as a basic system.

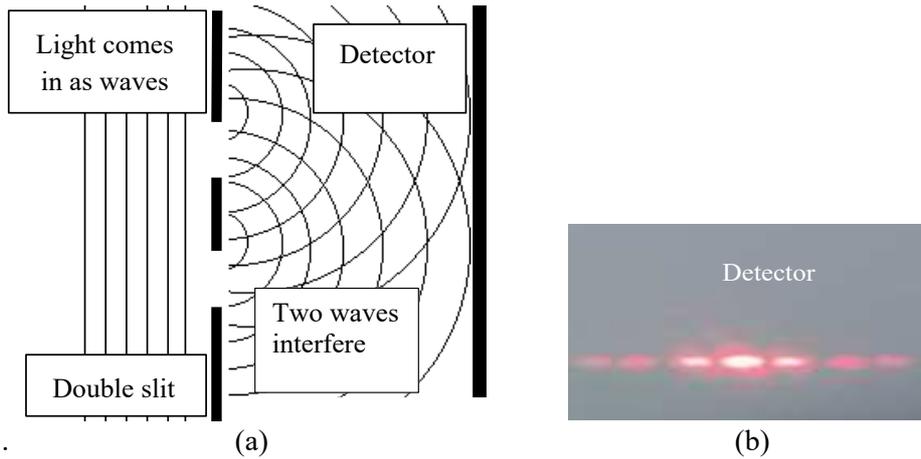


Figure 1 Standard Double slit Experiment

The standard understanding of double slit experiments is considered naturally self-evidence. Thus, when a photon lands on a detector as a particle, the concept of “wave function collapse” is introduced.

To precisely describe the double slit, we introduce a model, in which a slide of double slit and its right-side neighborhood is represented as a “virtual box” (Figure 2).

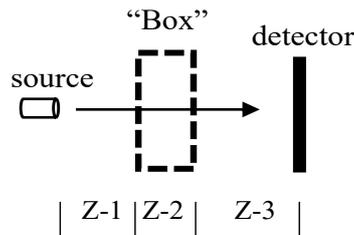
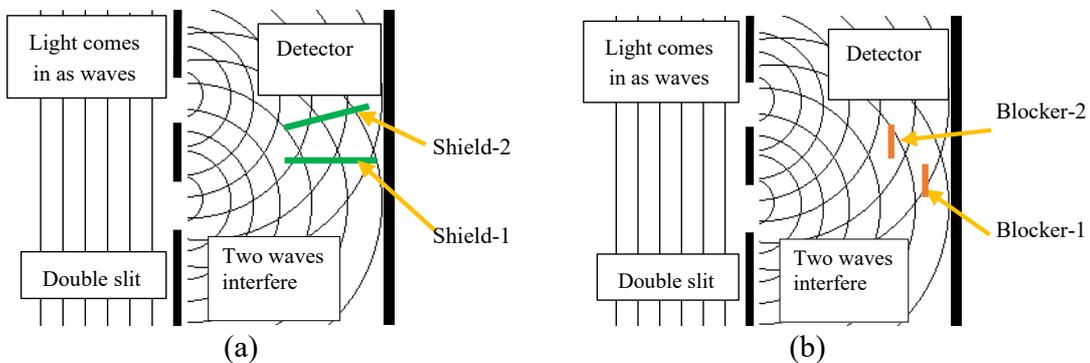


Figure 2 Double slit Apparatus with “virtual box”

Let’s divide the model into 3 zones, zone-1 (Z-1) is from source to the left side of the virtual box, the virtual box is zone-2 (Z-2), zone-3 (Z-3) is from the right side of the virtual box to detector.

In this article, we study, how photons behave in zone-1 and zone-3, and estimate the range of zone-2, the virtual box.

We start from the wave interpretation of the double slit experiments, and design experiments to test it. Thus, the schematic drawings in Figure 3 show that light behaves as waves in the entire experiment.



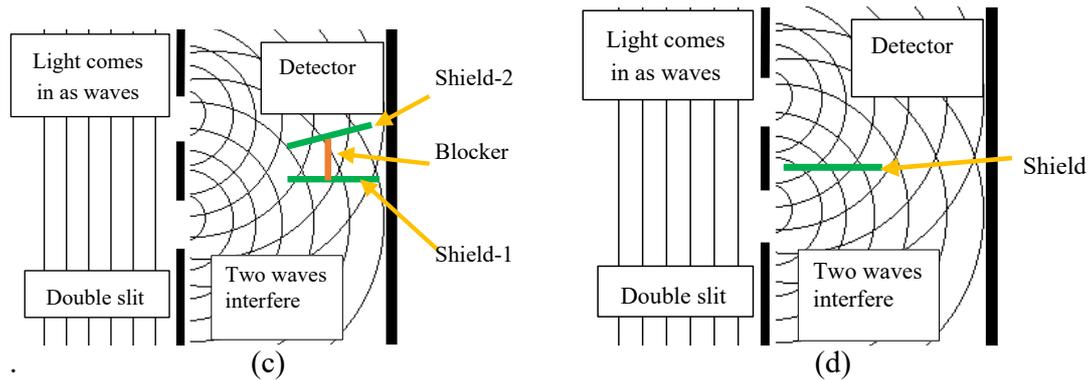


Figure 3 Schematic of Outline

To test whether photons behave as waves in zone-3, we insert: (1) longitudinal “wave shield(s)” (Figure 3a), denoted as shield; (2) transverse “wave blocker(s)” (Figure 3b), denoted as blocker; (3) combination of shield and blocker (Figure 3c); all near detectors. We want to observe whether the interference pattern would be disturbed under the situations shown in Figure 3. To test the right-side boundary of the virtual box, a shield is inserted and gradually move it closer to the double slit (Figure 3d) to determine where photons would start to change behaviors, if they would change.

Note that until this point, we assume that photons propagate as waves before and after passing through a double slit, and plan to test it.

However, in the rest of the article, we discover that photons behave as particles in zone-1 and zone-3. Thus, in the Figures below, wave-shape patterns are deleted.

### 3. Double slit Changing Photons’ Behavior

#### 3.1. Two Postulates

We propose two postulates related to double slit experiments and then test them.

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

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

One of the consequences of postulate-2 is that in zone-3, each fringe is formed independently and can be formed partially. Indeed, the experiments testing the consequence strongly support postulate-2.

First, let’s experimentally confirm a rule.

**Rule:** The particle nature of a single input beam of photons is not changed by a beam splitter (BS), either reflected by the BS or passing through the BS.

Example-1: 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.

Note that in this article, we do not discuss the situation of two input coherent beams; for example, two beams are inputted into an output beam splitter in a Mach-Zehnder interferometer.

Although the Rule seems trivial, it is utilized to prove postulate-1.

Let’s test the Rule experimentally.

**Experiment-1:** testing the Rule.

**Experimental Setup** (Figure 4a): photons reflected by both BS1 and a mirror, M1, land on detector-1 (D1), while photons passing through BS1 land on D2.

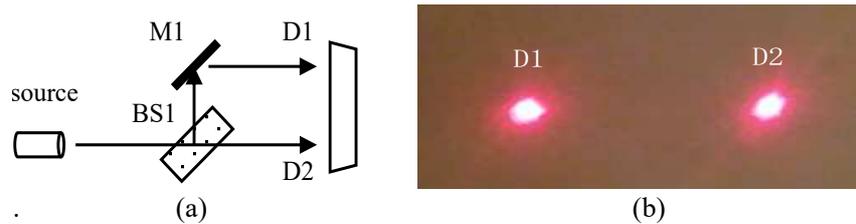


Figure 4 Testing Rule (1)

**Observation** (Figure 4b): D1 and D2 show the images of the source respectively, which indicate that photons detected on both D1 and D2 respectively have the same particle nature. The Rule is proved by experiment-1.

### 3.2 Photons Behaving as Particles before Arriving at Double Slit

Now let's test postulate-1 experimentally.

**Experiment-2:** testing postulate-1 with two setups.

**Experimental setup-1** (Figure 5a): Photons passing through both BS1 and BS2 strike at D2. Photons reflected by BS1 and M1 and passing through slide-1 strike at D1. Photons reflected by BS2 and M2 and passing through slide-2 strike at D3. All images are shown on the same detector to visually observe the phenomenon. To show the difference, we use a cross-double slit for slide-1 (Figure 5b) and a standard double slit for slide-2.

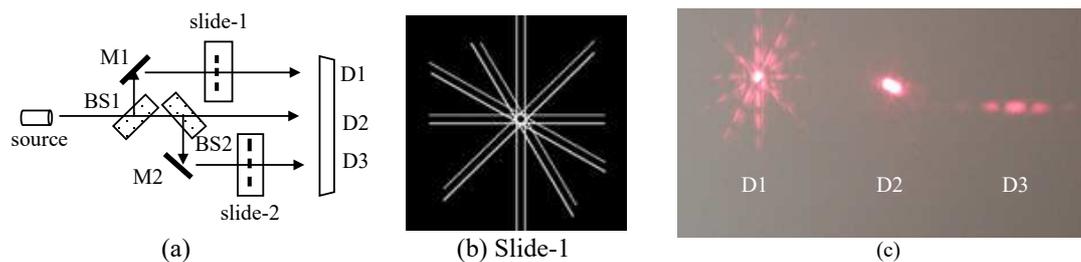


Figure 5 Testing Postulate-1 (I)

**Observations** (Figure 5c): D2 displays the image of the source, i.e., photons passing through BS1 and BS2 behave as particles. Thus, according to the Rule, photons reflected by BS1/M1 and BS2/M2 traveling towards slide-1 and slide-2 behave as particles. Namely, photons behave as particles before arriving double slit/cross-double slit, although D1 and D3 show interference patterns created by the cross-double slit and the double slit, respectively.

**Experimental setup-2** (Figure 6a): Photons passing through both BS1 and slide strike at D2. Photons reflected by BS1 and M1 strike at D1. We use a cross-double slit for slide (Figure 6b).

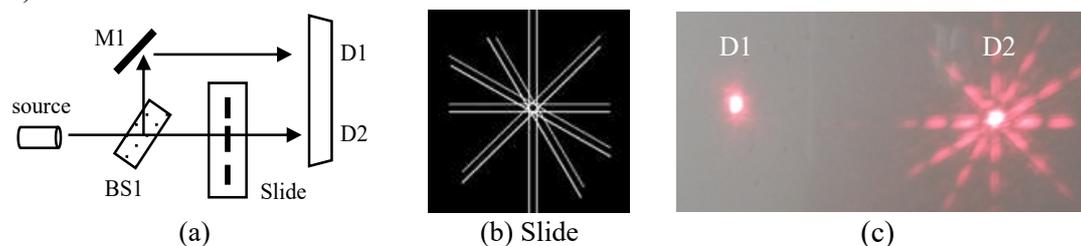


Figure 6 Testing Postulate-1 (2)

**Observation** (Figure 6c): D1 shows the image of the laser source, which indicates the particle nature. D2 is an interference pattern created by the cross-double slit.

We Conclude:

- (1). D1 shows the particle nature of photons. According to the Rule, reflection by BS1 does not affect the nature of photons; thus, photons from the source to D1 behave as particles.
- (2). According to the Rule, passing through BS1 does not affect the nature of photons; thus, the nature of photons passing through BS1 towards the slide is the same as that of photons reflected by BS1, i.e., behave as particles. Before striking on the slide of cross-double slit, photons behave as particles.

Postulate-1 is proven, i.e., before passing through a double slit/cross-double slit, photons behave as particles.

Now we have two facts:

- (A) It is well known that after passing through a double slit/cross-double slit, a photon is always absorbed at the discrete points of the detector, as individual particle, i.e., the interference pattern appears via the varying density of these particle hits on the detector; and
- (B) We proved that before striking at a double slit/cross-double slit, photons directly from a laser source behave as particles.

Thus, the standard interpretation of double slit experiment is challenged.

### 3.3. Photons Behaving as Particle before Landing on Detector

Now let's test postulate-2 experimentally. Note that since we will prove that photons behave as particles in Z-3, in the following schematic drawings, we will not draw wave-shape patterns as we did in Figure 3. Note that schematic drawings below are not to scale.

#### 3.3.1. Testing Postulate-2 with Longitudinal Shields

##### Experiment-3: Testing Postulate-2 with Single Shield

**Experimental Apparatus:** Inserting a "shield" (green colored) made of carboard into the apparatus of the regular double slit experiments between the double slit and detector. The purpose is to test whether the shield would 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. Shield-1 is assumed to separate waves and thus prevent waves from interfering. An analogy is a breakwater that break water waves.

**Experimental setup-1** (Figure 7a): Shield-1 contacts the detector.

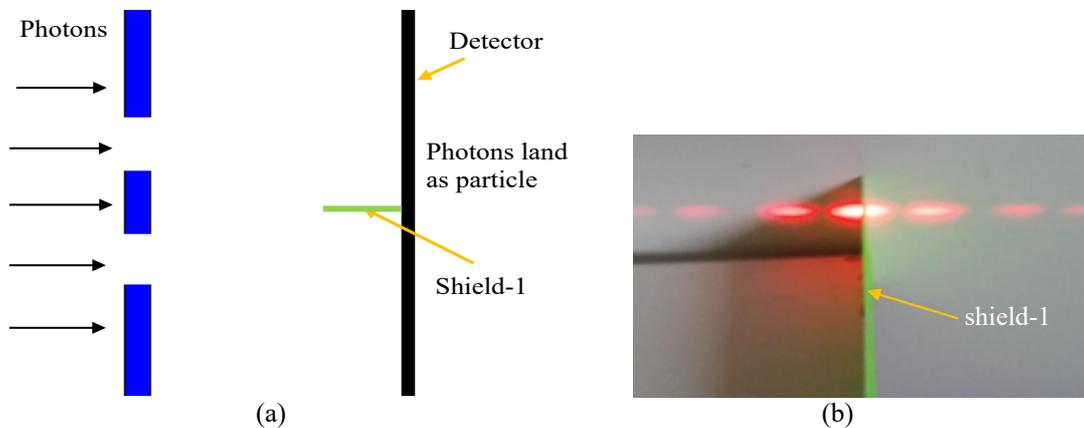


Figure 7 Testing Postulate-2 with Single Shield (I)

**Observation** (Figure 7b): Shield-1 does not affect the interference pattern at all, which would not be expected if photons behave as waves.

**Experimental setup-2** (Figure 8a): Shield-1 is one inch away from detector.

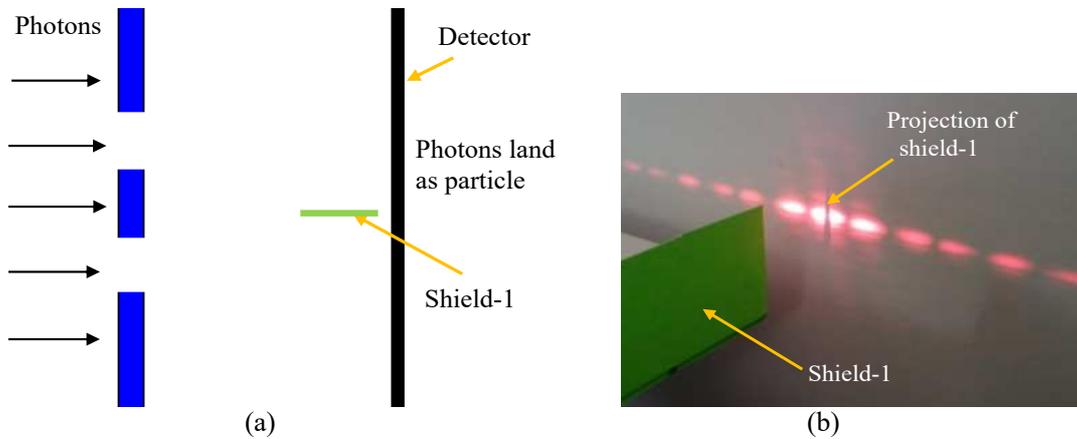


Figure 8 Testing Postulate-2 with Single Shield

**Observation** (Figure 8b): Shield-1 does not affect the interference pattern at all. The projection of shield-1 shows on the detector, which would not be expected if photons behave as waves.

**Experiment-4: Testing Postulate-2 with Two Shields**

**Experimental apparatus:** Inserting shield-1 and shield-2 into the apparatus of the regular double slit experiments between the double slit and detector. 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.

For simplicity, shield-1's orientation is from the center of the double slit points to the center of the zeroth-order-fringe, while shield-2 is along the line between the center of the double slit and the center of the first-order fringe. We refer shield-1 and shield-2 as longitudinal. Both shields are 28 inches long, 1.5 inch wide, and 0.3 mm thick. The distance between the double slit and the detector is 200 inches.

Both shields are assumed to separate waves and thus prevent waves from interfering.

The experiment is carried out in four setups.

**Experimental setup-1** (Figure 9a): Both shield-1 and shield-2 contact the detector.

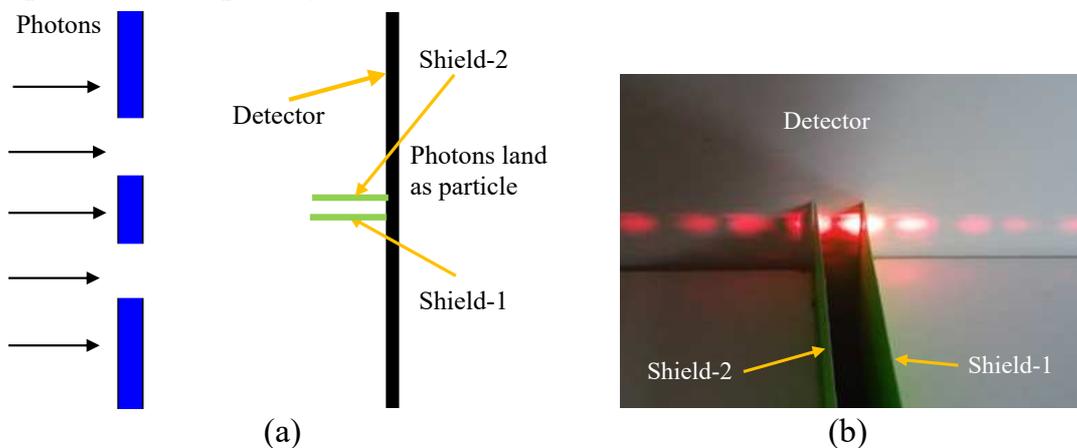


Figure 9 Testing Postulate-2 with Two Shield (I)

**Observation** (Figure 9b): We observe the interference pattern, which is exactly 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 at all, which

indicates that photons do not behave as waves, at least within 28 inches of the detector. Otherwise, light waves should be prevented from interfering with each other, and the “interference” pattern should be disturbed, especially the zeroth-order and first-order fringes. **Experimental setup-2** (Figure 10a): Moving both shield-1 and Shield-2 back one inch from the detector.

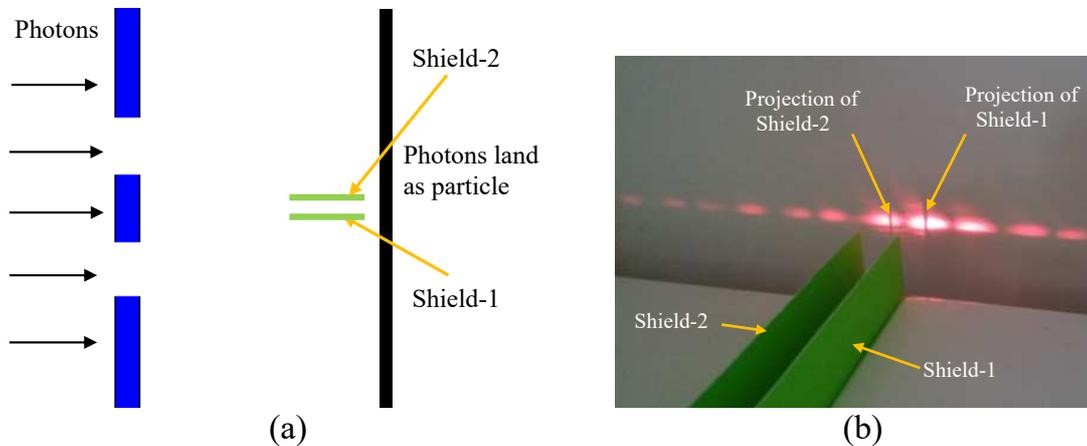


Figure 10 Testing Postulate-2 with Two Shield (II)

**Observation** (Figure 10b): the interference pattern has no change, i.e., the interference pattern is the same as if there were no shield-1 and shield-2. 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 pass through the narrow channel, strike at the positions of the zeroth-order fringe and first-order fringe on the detector, and form two projections, while not disturbing the existing interference pattern.

**Experimental setup-3** (Figure 11): Two shields 70 inches long contacted to the detector, which formed a long narrow channel. Note that the picture was shot from the “Entrance” to the detector so that the interference pattern shows on the same picture and thus, Entrance looks wider.



Figure 11 Testing Postulate-2: Two 70 Inches Shields (IV)

**Observation:** 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, which would be expected only if photons behave as particles.

**Experimental setup-4** (Figure 12a): Shield-2 is placed at 60 inches from double slit; shield-1 stays at the same position as in Figure 10a.

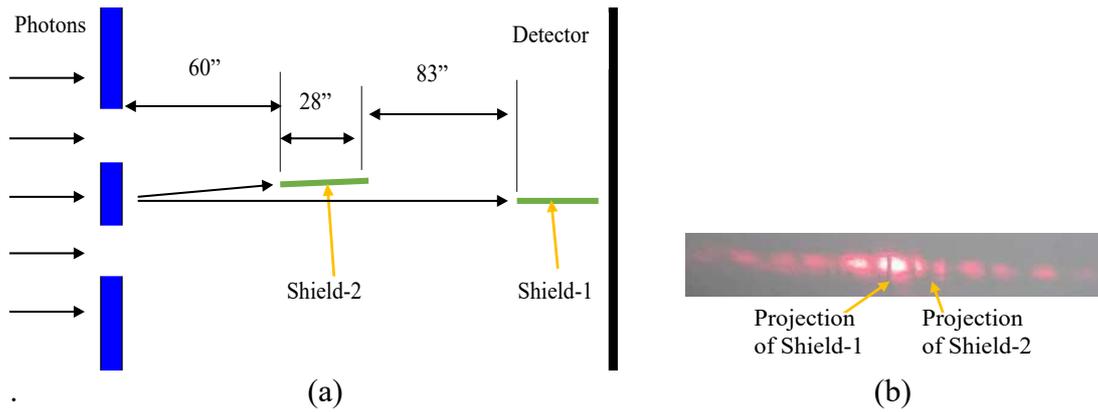


Figure 12 Testing Postulate-2 with Two Shields (V)

**Observation** (Figure 12b): 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.

Comprehensive-double slit experiments have been carried out: at positions of different distances from the detector, for example, 40 inches, 80 inches, and 120 inches. We always observe the same interference patterns and projections of shield-1 and shield-2.

**Conclusion:** Only particles can pass through the long and narrow channel between shield-1 and shield-2, and form fringes on the detector; thus, photons behave as particles long before landing on the detector. The concept of “wave function collapse” is not necessary.

Postulate-2 is proved experimentally.

In contrast, photons distribute with a wave-like interference pattern on the detector.

This is a paradox.

We discuss this paradox later and provide an interpretation.

### 3.3.2 Testing Postulate-2 with Transverse Blockers.

**Experiment-5:** Testing Postulate-2 with Blockers

Let us consider five experimental setups.

**Experimental Setup-1** (Figure 13a): blocker-10, blocker-11 and blocker-12, each is 0.5-inch wide, are placed along the normal vector of the surface of detector, and separated by 4 inches.

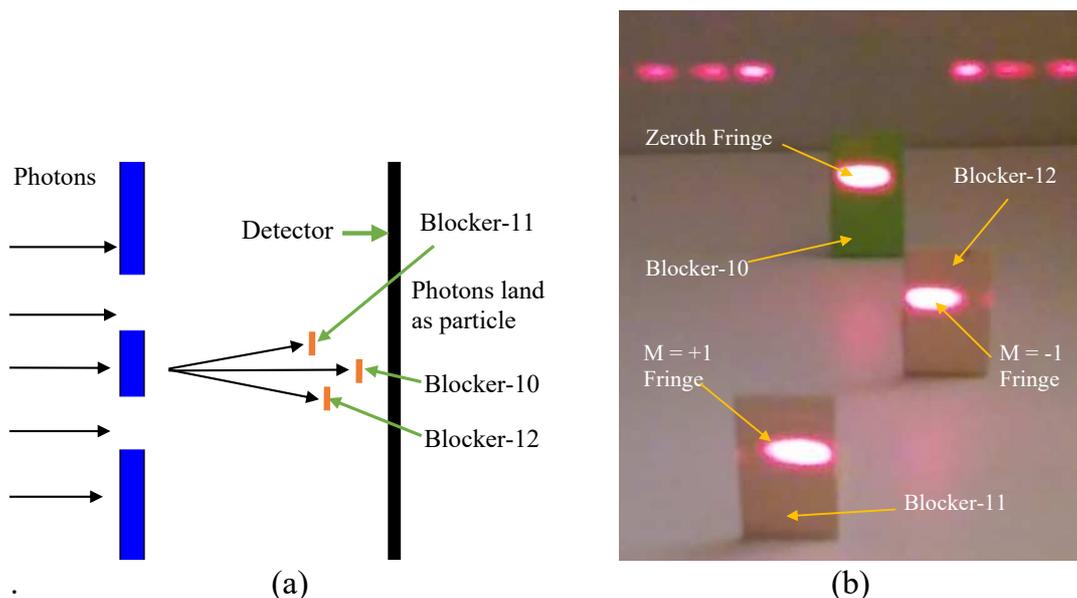


Figure 13 Schematic Setup and Observation

**Observation** (Figure 13b): 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 the detector. Namely, fringes are formed independently.

**Experimental Setup-2** (Figure 14a): blocker-11 and blocker-12 are utilized.

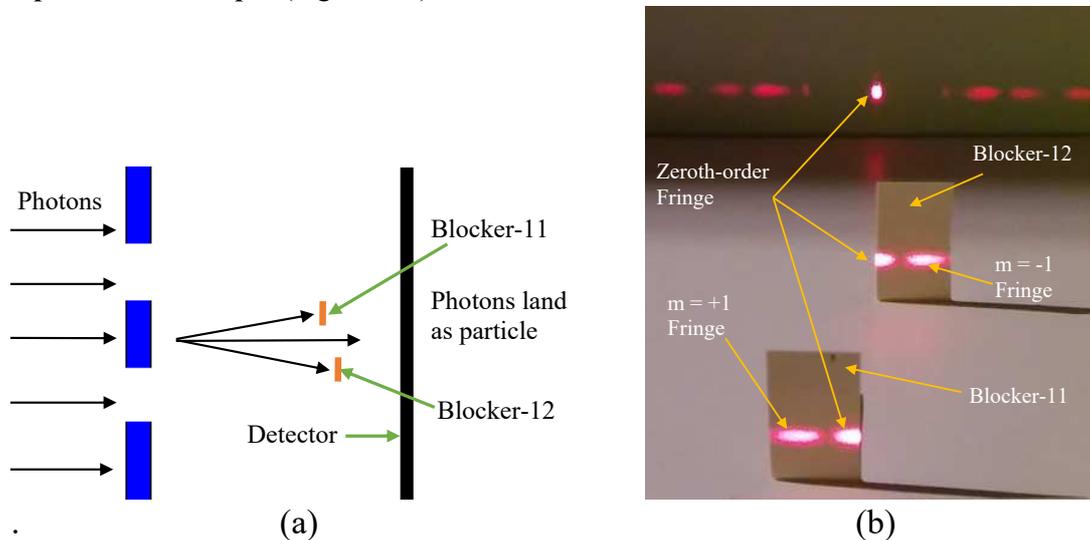


Figure 14 Fringes Formed Independently and Partially

**Observation** (Figure 14b): 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 detector. Namely, fringes are formed independently.

**Experimental Setup-3** (Figure 15): blocker-11 and blocker-12 are placed differently.

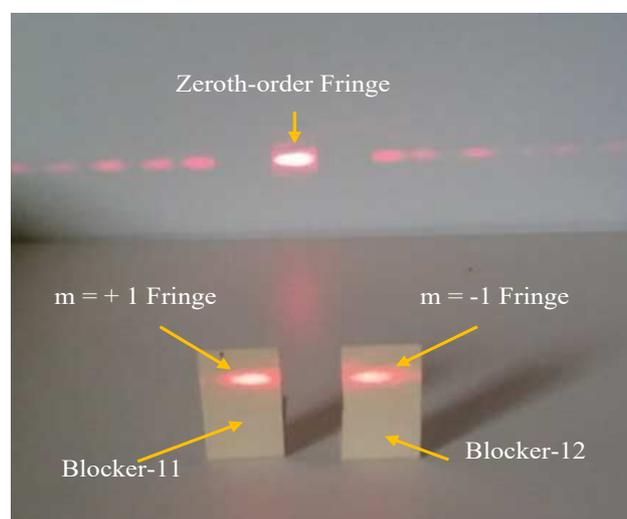


Figure 15 Fringes Formed Independently

**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 16): blocker-11 and blocker-12 are placed along the normal vector of the surface of detector, and separated by 4 inches.

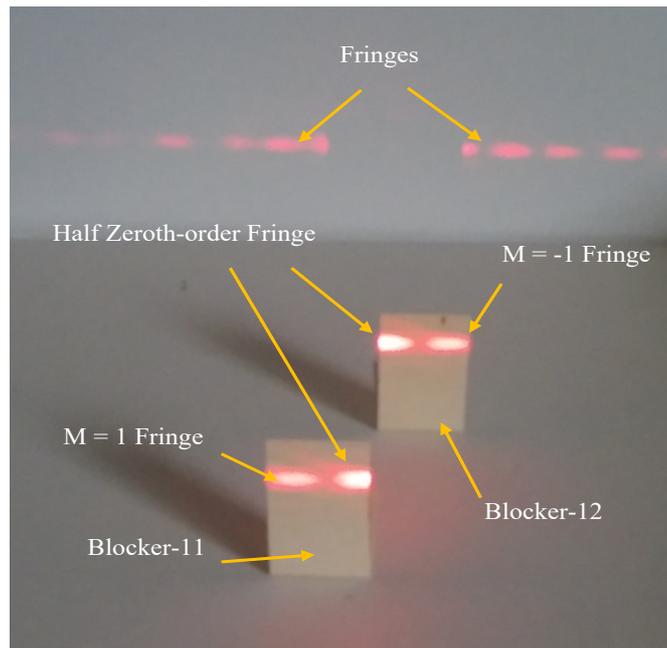


Figure 16 Fringes Formed Independently and partially

**Observation** (Figure 16): 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 17): blocker-11 and blocker-12 are placed along the normal vector of the surface of detector, and separated by 4 inches.

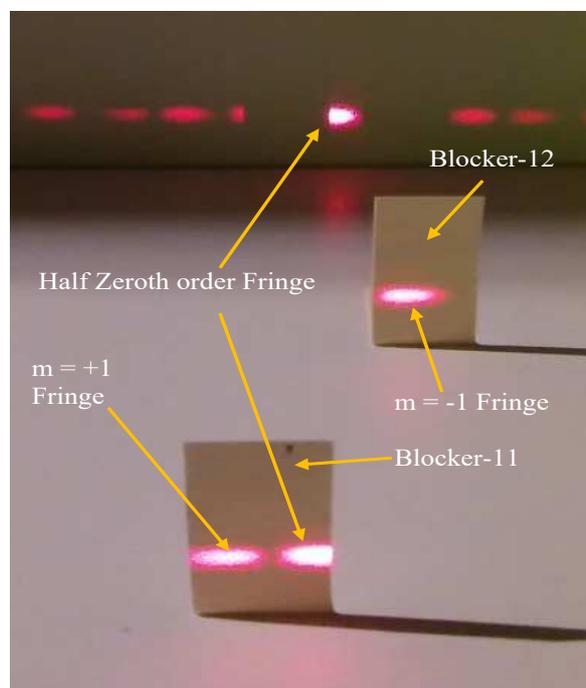


Figure 17 Fringes Formed Independently and partially

**Observation** (Figure 17): 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 can be formed partially, which would be expected only if photons behave as particles in Z-3. Postulate-2 is proved.

In contrast, photons are distributed with a wave-like interference pattern on the detector.

This is a paradox.

We discuss this paradox later and provide an interpretation.

Note that one can consider each blocker as a measurement device to detect the nature of photons, while without disturbing the interference pattern.

### 3.3.3. Testing Postulate-2 with Combinations of Longitudinal Shields and Transverse Blocker.

We have shown that, on the one hand, longitudinal shield-1 and shield-2 do not disturb the interference pattern in zone-3 at all. On the other hand, blockers do block the propagation of photons as photons are particles. Now let's test what are the effects of combinations of shields and blockers.

**Experiment-6:** Testing Postulation-2 with Single Shield and blocker

**Experimental Setup** (Figure 18a): Shield is one inch away from detector. A blocker is placed next to the shield.

**Observation** (Figure 18b): (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 the a first-order fringe.

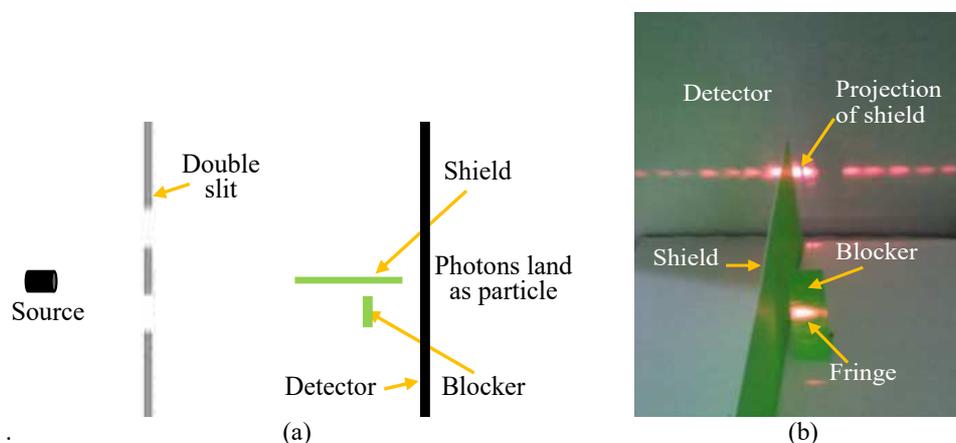


Figure 18 Testing Postulate-2 with Single Shield and Blocker

The fringes are formed independently. Above phenomena would be expected only if photons behave as particles.

**Experiment-7:** Testing Postulation-2 with Two Shield and Blocker

**Experimental Setup** (Figure 19a):

Now let us place blocker-1 at the other end of shield-1 and shield-2, where we denote it as Entrance, i.e., photons enter the narrow channel between shield-1 and shield-2 from there (Figure 19a). The interference pattern is formed on blocker-1 instead of the detector (Figure 19b).

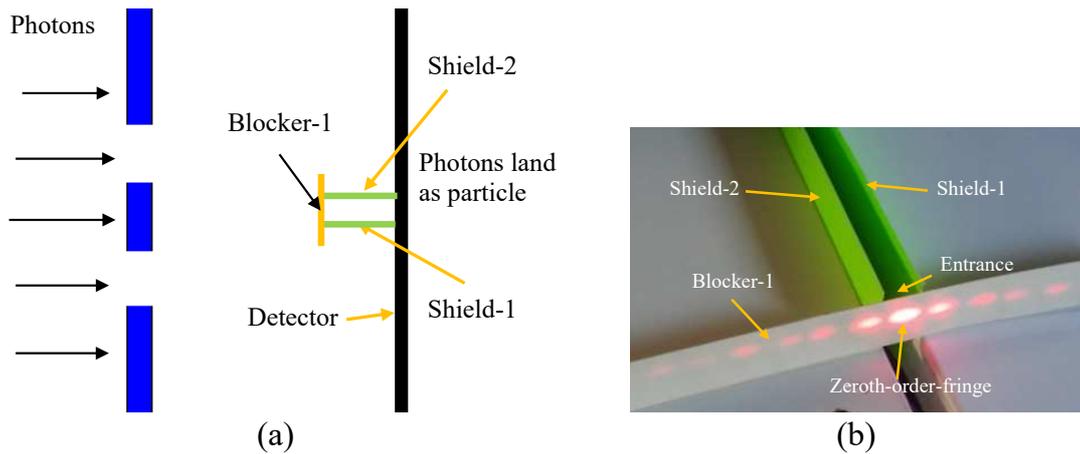


Figure 19 Shields and Blocker

We perform this experiment in two setups.

**Experimental Setup-1** (Figure 20a): Cutting the top portion of blocker-1.

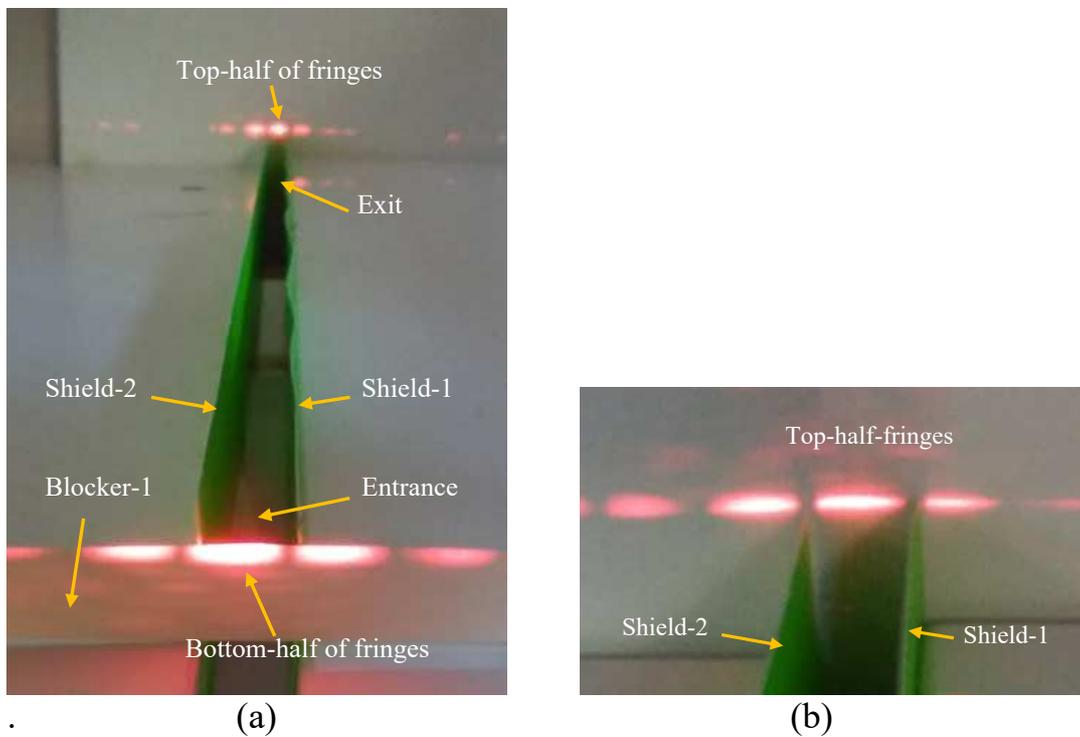
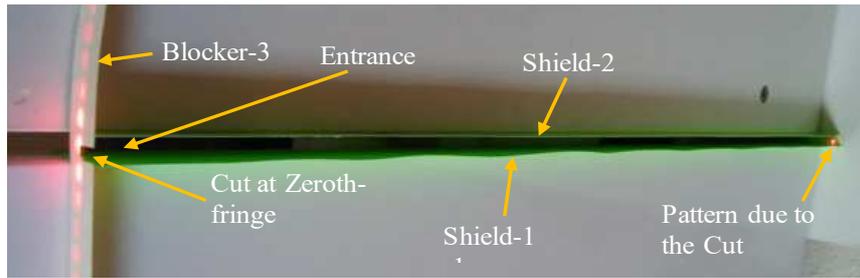


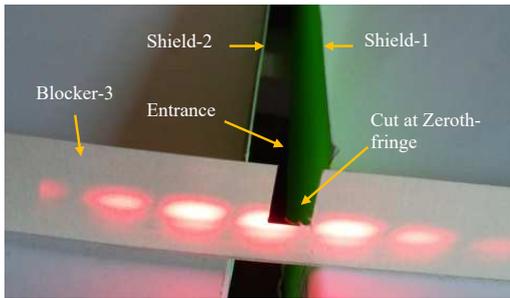
Figure 20 Cut Top Half of Blocker-1 and Pattern

**Observation** (Figure 20b): the bottom half of the fringes are still on blocker-1, while the top half are on the detector. Namely fringes can be formed partially. And shields have no effect at all.

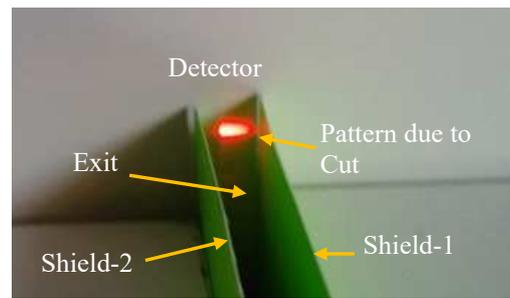
**Experimental Setup-2** (Figure 21a and Figure 21b): cut a “U” shape gap at the position of the zeroth-order fringe on blocker-3.



(a)



(b)



(c)

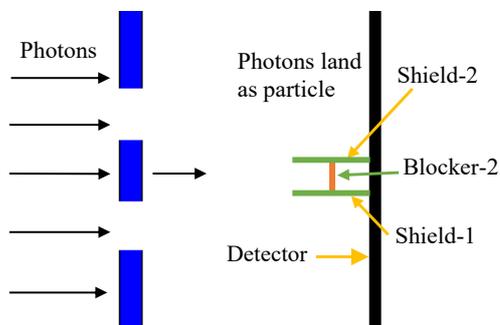
Figure 21 Blocker-3 with Cut

**Observation** (Figure 21b and 21c): Photons pass through the cut and form the exactly same shape of patterns on the detector, which shows the particle nature of light and indicates that photons move along straight lines.

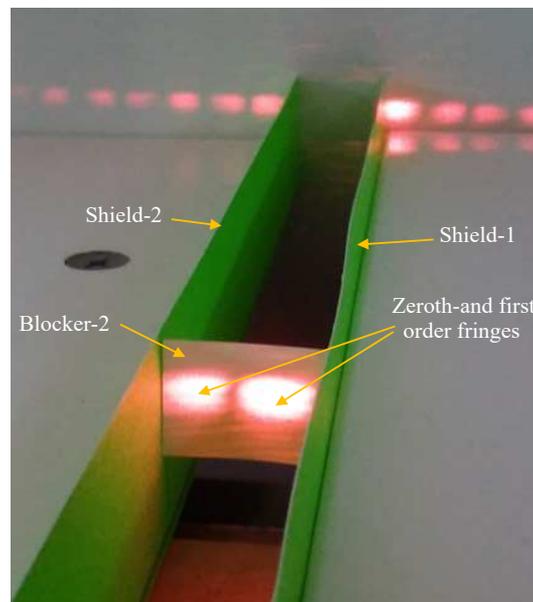
**Experiment-8:** Testing Postulate-2.

We perform this experiment in two setups.

**Experiment Setup-1** (Figure 22a): insert transverse blocker-2 one inch wide into the channel formed by shield-1 and shield-2 that are contact the detector.



(a)



(b)

Figure 22 Blocker-2 in Channel

**Observation** (Figure 22b): 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 at all. This observation indicates that photons behave as particles.

**Experimental Setup-2** (Figure 23): cut two triangles on blocker-2 at the locations of the zeroth-order fringe and the first-order fringe. Then insert blocker-2 into the channel.

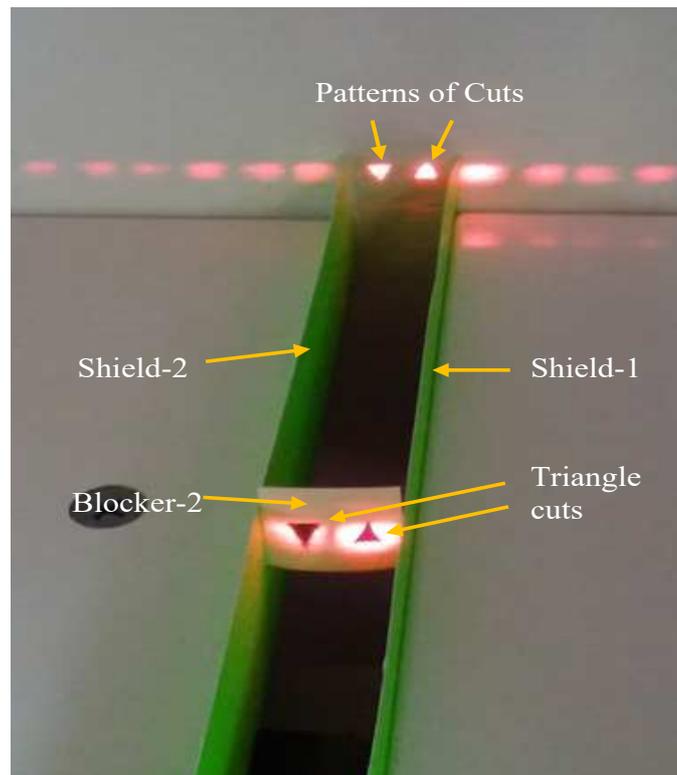


Figure 23 Blocker-2 with Two Cuts

**Observation** (Figure 23): 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 and shows that photons move along straight lines. Note that photons are not directly from the source; they just pass through a double slit and form the interference fringes. If photons would behave as waves, this phenomenon would not be explained.

In contrast, photons are distributed with a wave-like interference pattern on the detector. This is a paradox.

We discuss this paradox later and provide an interpretation.

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

The 1D-double slit apparatus/experiments have been extended to 2D-cross-double slit apparatuses/experiments [15] [16], which have many varieties. Without losing generality, we perform comprehensive-double slit experiments with cross-double slit.

**Experiment-9:** Testing Postulate-2

**Experimental Setup-1** (Figure 24): shield-1 and shield-2 contact the detector and form a narrow channel.

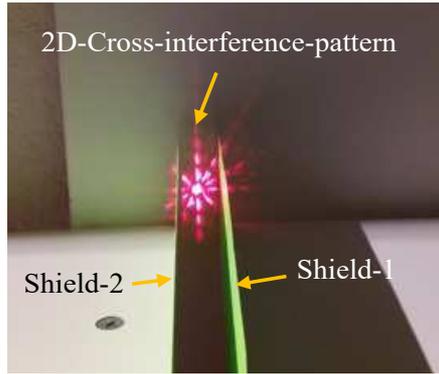


Figure 24 2D-pattern with Channel

**Observation:** the channel does not disturb the interference pattern at all.

**Experimental setup-2** (Figure 25a): using blocker-3 to block the bottom portion of the 2D-interference pattern.

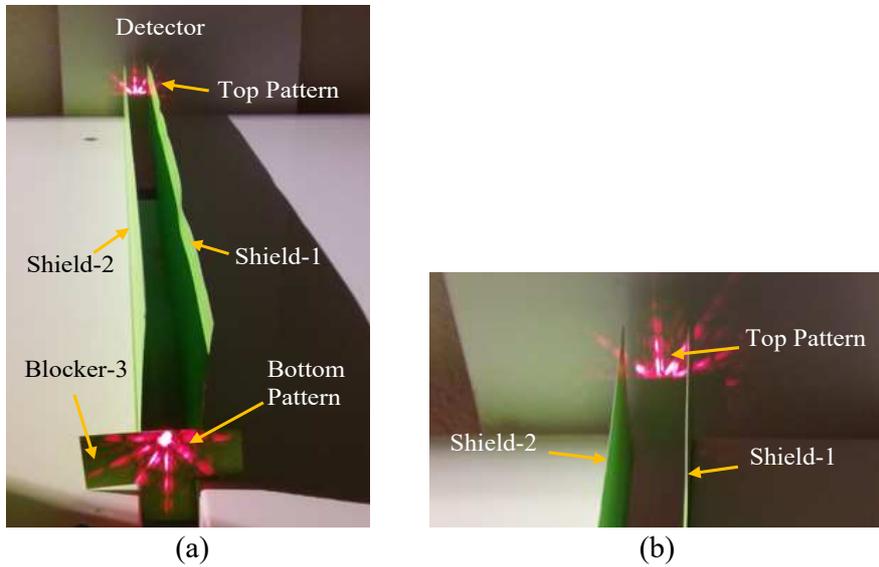


Figure 25 Testing Postulate-2 with Cross-double slit

**Observation** (Figure 25): the top portion of the 2D interference pattern is shown on the detector (Figure 25b), while the bottom portion is shown on blocker-3. Namely, 2D patterns are created independently and partially. Only particles can do that.

Postulate-2 is proved experimentally: in zone-3, photons move along predetermined trajectories that are straight lines and behave as particles.

**Experimental setup-3** (Figure 26a): using blocker-3 to block bottom-right corner of the 2D-interference pattern.

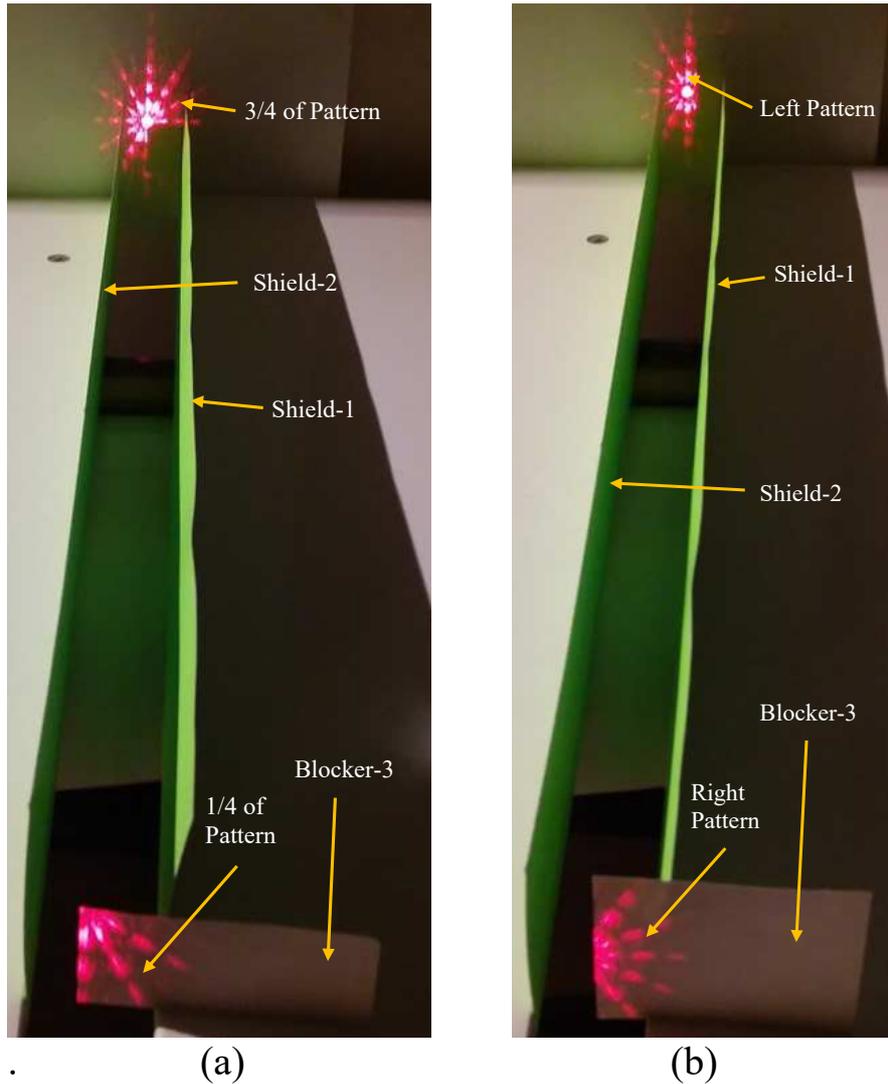


Figure 26 Testing Postulate-2 with Cross-double slit

**Observation** (Figure 26a): the  $\frac{3}{4}$  portion of the 2D interference pattern shown on the detector (Figure 26a), while the bottom-right portion of the interference pattern shows on blocker-3.

**Experimental setup-4** (Figure 26b): using blocker-3 to block right portion of the 2D-interference pattern.

**Observation** (Figure 26b): the left portion of the 2D interference pattern shown on the detector, while the right portion of the interference pattern shows on blocker-3.

Namely, 2D patterns are created independently and partially. Only particle can do that.

### 3.3.5. Testing Range of Virtual Box

**Experiment-10:** searching the range of the Virtual Box.

**Experimental Setup** (Figure 27a): Moving a shield towards the double slit and observing. In this article, the shield is stopped at a position 2.5 cm from the double slit.

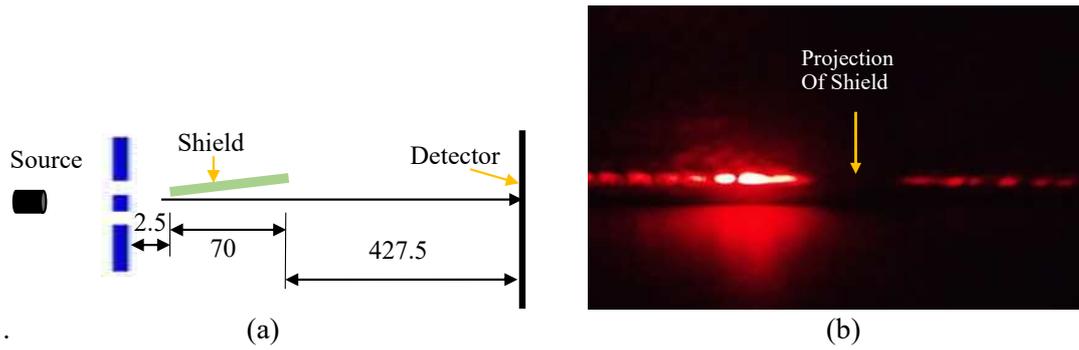


Figure 27 Schematic Setup and Observation (Unit: cm)

**Observation** (Figure 27b): both the “interference” pattern and the projection of the shield are show on the detector, the latter is much wider. Thus, the width of zone-3 is at least 497.5 cm, in which photons behave as particles.

Now let’s calculate the width of the projection of the shield on the detector.

In this case the cross section of the shield plays the role of a blocker.

The regular equation holds,

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

For our experiment, the wavelength is 650 nm, the distance from the double slit to one end of the cardboard is 2.5 cm, the spacing between two slits is 0.25mm, and the cross-section, thickness, of the cardboard is 0.3 mm. Substituting into Eq. (1), we obtain  $m \approx 4.6$ , namely up to the 4<sup>th</sup> bright fringes are all blocked by the cross section of the shield.

Note that if one performs which-path experiment in Z-2, the virtual box, the detection destroys the process of forming/grouping and thus, no interference pattern.

#### 4. Discussion

On the one hand, in the double slit experiments, it is interpreted that the light behaves as a wave and creates an interference pattern on a detector, which would not be expected if light behaves as particle. Indeed, the interference patterns do exist in the comprehensive-double slit experiments.

On the other hand, we have discovered experimentally novel phenomena that, in zone-3 of the double slit apparatuses, photons indeed behave as particles, which would not be expected if photons behave as waves.

This seems a paradox.

We suggest an interpretation to address this paradox. A laser source emits photons as a beam of particles (as proved experimentally when testing postulate-1). Those photons travel into the virtual box. In the language of “wave”, the function of the “virtual box” is a process of “forming” the distribution of photons as waves inside the “virtual box”. In the language of “particle”, the function of the “Virtual box” is a process of “grouping” photons into different groups/streams (denoted the process as “grouping”), which correspond to different fringes respectively. Photons landing on the same fringe are defined as “in the same group”. In practice, a “group” of photons propagates as a stream of particles and arrives at the same fringe continuously. Therefore, different groups/streams corresponding to different fringes are formed inside the virtual box. Where the process completed, either in “wave language” or in

“particle language”, is defined as the right-side boundary of the virtual box. When coming out of the “virtual box”, photons behave as groups/streams of particles (as proved experimentally when testing postulate-2), and follow the trajectories that lead to the different fringes. Although the trajectory of each photon cannot be determined, the trajectory of each group/stream of photons is determined while they are inside the “virtual box”. The trajectories of each group/stream of photons are shown by the evolution of each fringe after photons coming out the “virtual box”. However, the trajectories cannot be directly observed at the right-side boundary of the “Virtual box”, because existing observation equipment can only register photons, but cannot detect the directions of each group/stream of photons simultaneously. The right-side boundary is a point at which, different groups/streams of photons separate. One can observe the patterns only when different groups/streams of photons separate. The mechanism of “forming” or “grouping” is mystery.

Note that in which-path experiments, the measurements are made in the virtual box, Z-2, thus disturb the process of “forming” or “grouping”. As a consequence, no interference pattern would be formed on the detector/screen. However, if the measurements are done in Z-3, the interference distribution still exists. As we did in the comprehensive-experiments, each blocker can be considered as a measurement tool and does not affect the interference distribution at all.

Based on comprehensive-double slit experiments, we suggest that (1) the above experiments indicate that the “particle nature” of photons is intrinsic; and (2) restudy the mystery of double slit experiments, complementarity principle and wave-particle duality.

## **5. Conclusion**

We propose and perform comprehensive-double slit/cross-double slit experiments with simple apparatuses to study the basic quantum mystery. Novel phenomena are discovered, which are naked-eye-visible.

Based on three facts discovered from above experiments, (1) shields have no “wave shielding effect” on fringes, i.e., there is no wave in Z-3; (2) each fringe is formed independently; (3) each fringe can be formed partially, we conclude that, before landing on the detector/screen, i.e., in zone-3, photons behave as particles. Namely, for the double-slit experiments, the introduction of the “wave function collapse” at the detector is not necessary. We also show that, before arriving at a slide of double slit/cross-double slit, photons behave as particles.

Now, we obtained more complex and comprehensive experimental data, which suggest a criterion on interpretations of the phenomena.

## **Appendix:**

### **A1. Cross-double slit**

Let us review cross-double slit apparatus that can be used in comprehensive double slit experiments.

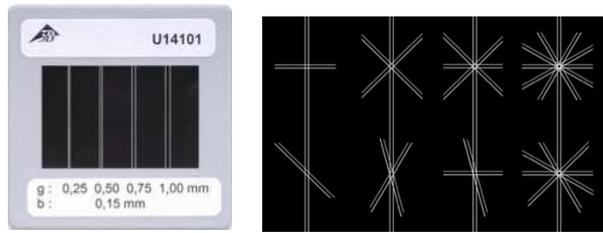


Figure A1 Double slit vs. Cross-Double slit

Figure A1 compares a slide of standard double slit with a slide of cross-double slit. Next show a standard double slit/interference pattern and some of cross-double slit/interference patterns without detail discussion.

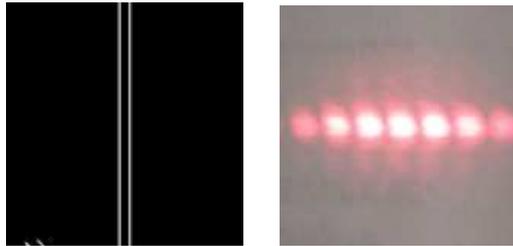


Figure A2 One double slit and pattern

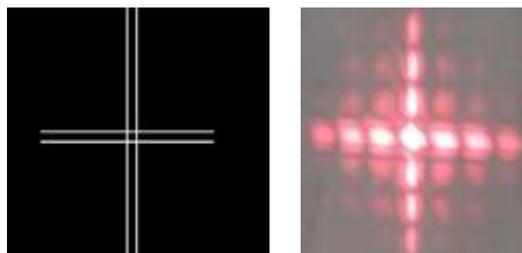


Figure A3 Two crossing double slits and interference pattern

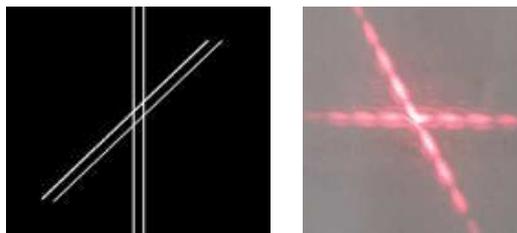


Figure A4 Two crossing double slits and interference pattern

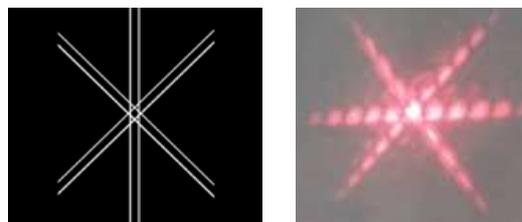


Figure A5 Three crossing double slits and interference pattern

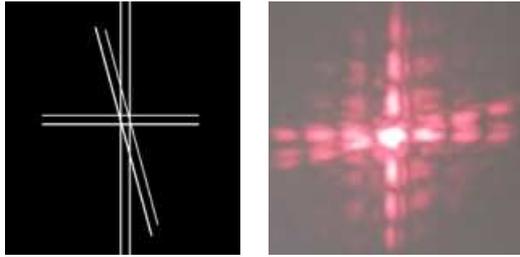


Figure A6 Three crossing double slits and interference pattern

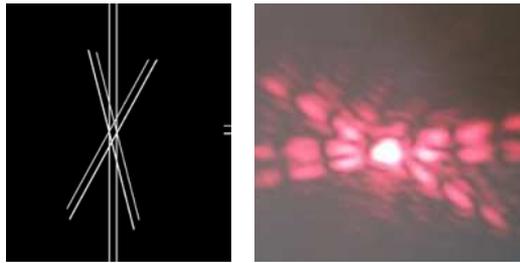


Figure A7 Three crossing double slits and interference pattern

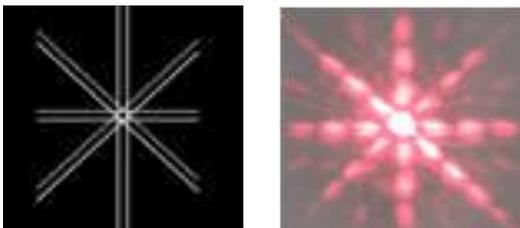


Figure A8 Four crossing double slits and interference pattern

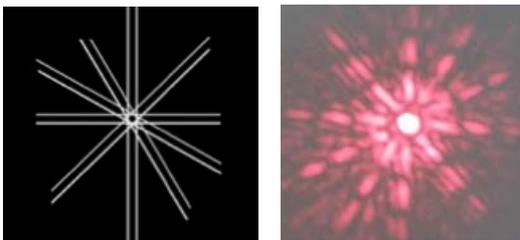


Figure A9 Five crossing double slits and interference pattern

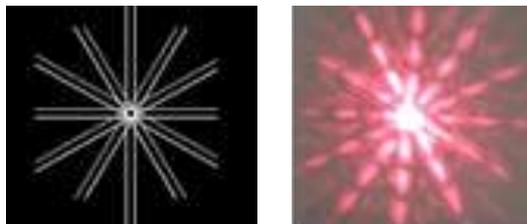


Figure A10 Six crossing double slits and interference pattern

There are many more varieties of cross-double slit apparatuses, either with different numbers of double slits crossing together, or crossing at different angles, etc. Mathematically

interpreting observations consistently is a challenge. The cross-double slit experiments are more mysterious than the standard double slit experiments.

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- [17] Hui Peng, “Observation of Which-Way-2D-Cross-Double-Slit Experiments: Violation of Bohr’s Complementarity Principle”, *Inter. J. of Phys.* **2020**, 8(4), 153-157.

# Figures

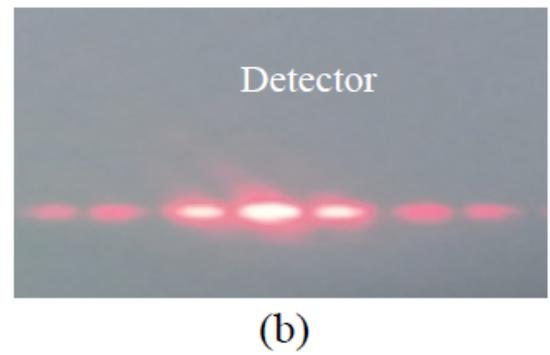
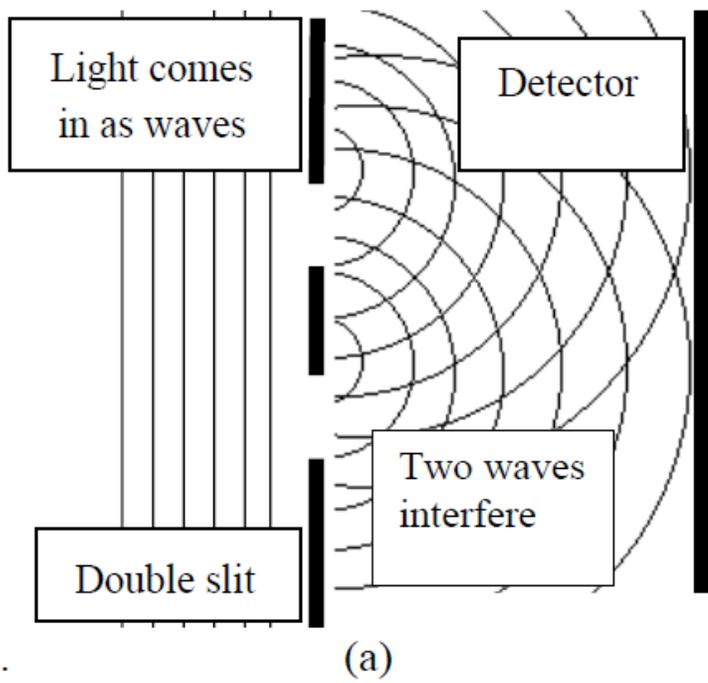


Figure 1

Standard Double slit Experiment

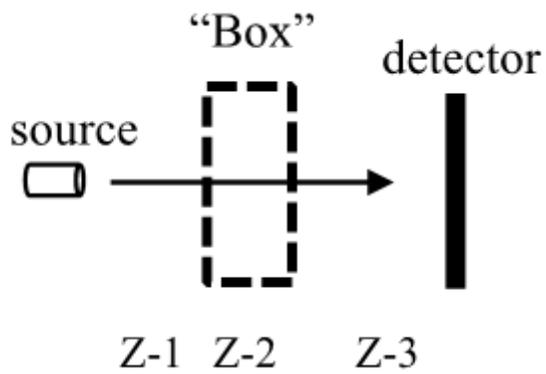


Figure 2

Double slit Apparatus with "Virtual box"

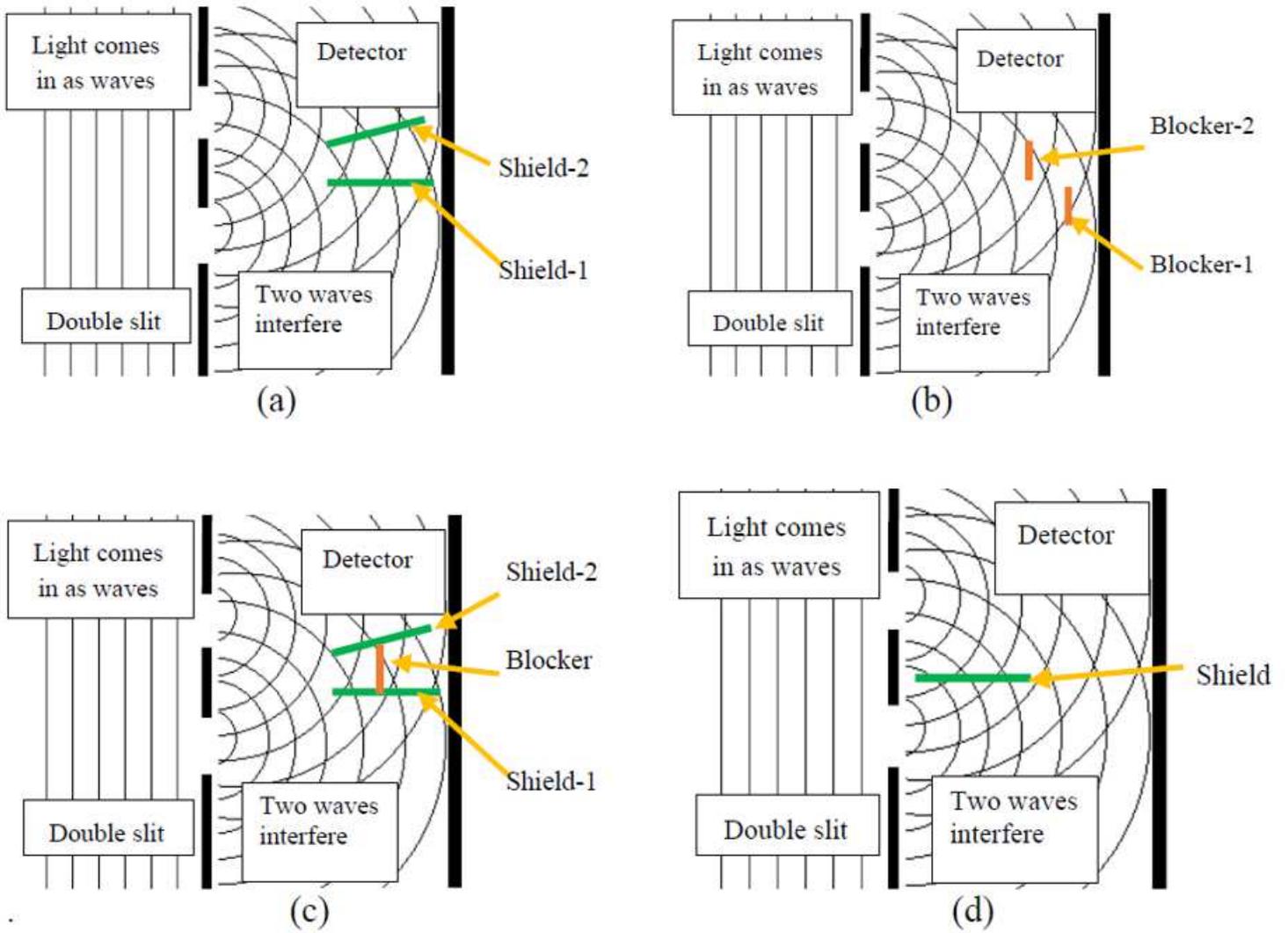


Figure 3

Schematic of Outline

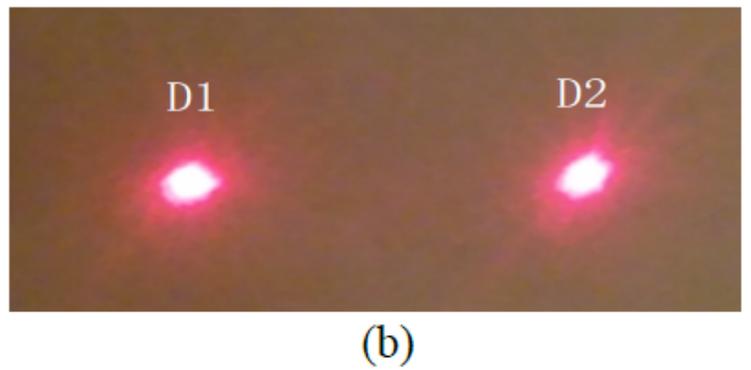
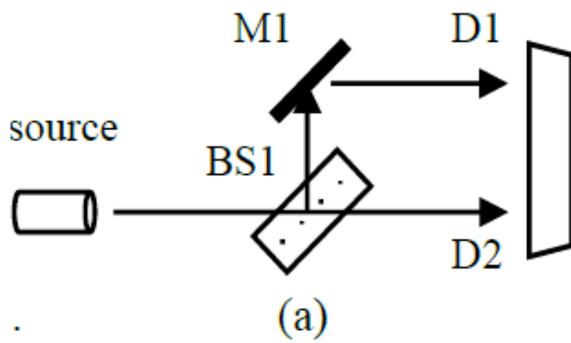


Figure 4

Testing Rule (1)

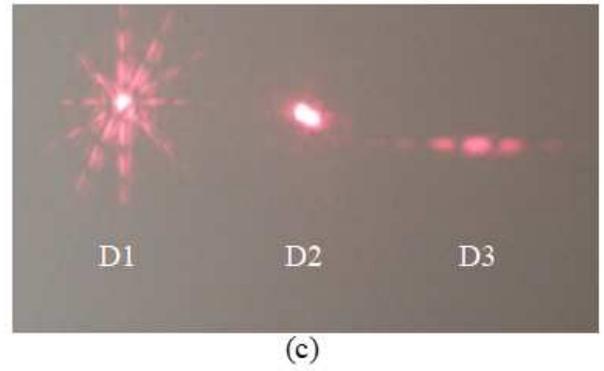
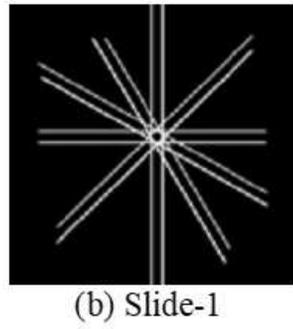
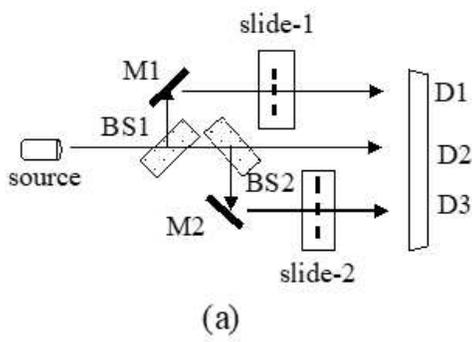


Figure 5

Testing Postulate-1 (1)

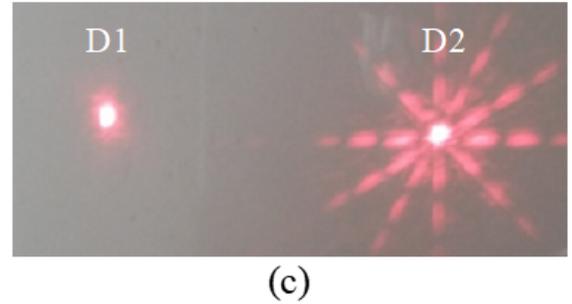
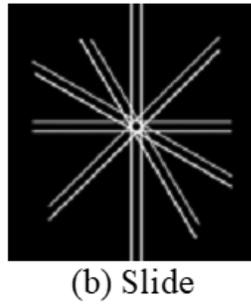
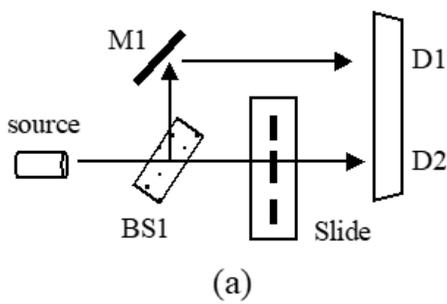


Figure 6

Testing Postulate-1 (2)

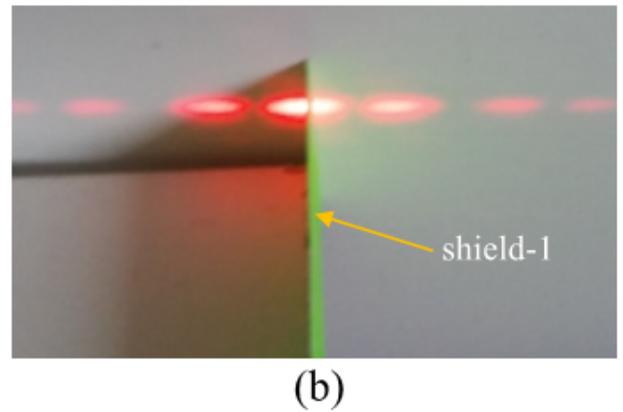
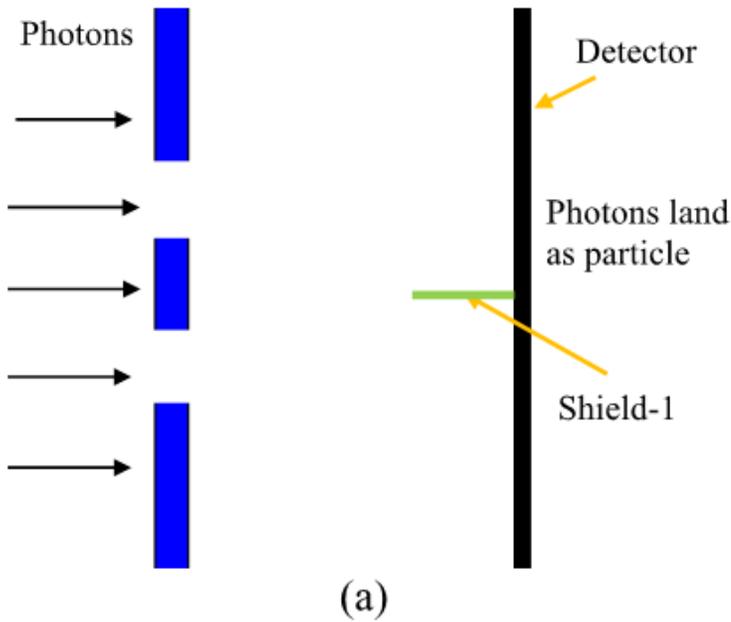


Figure 7

### Testing Postulate-2 with Single Shield

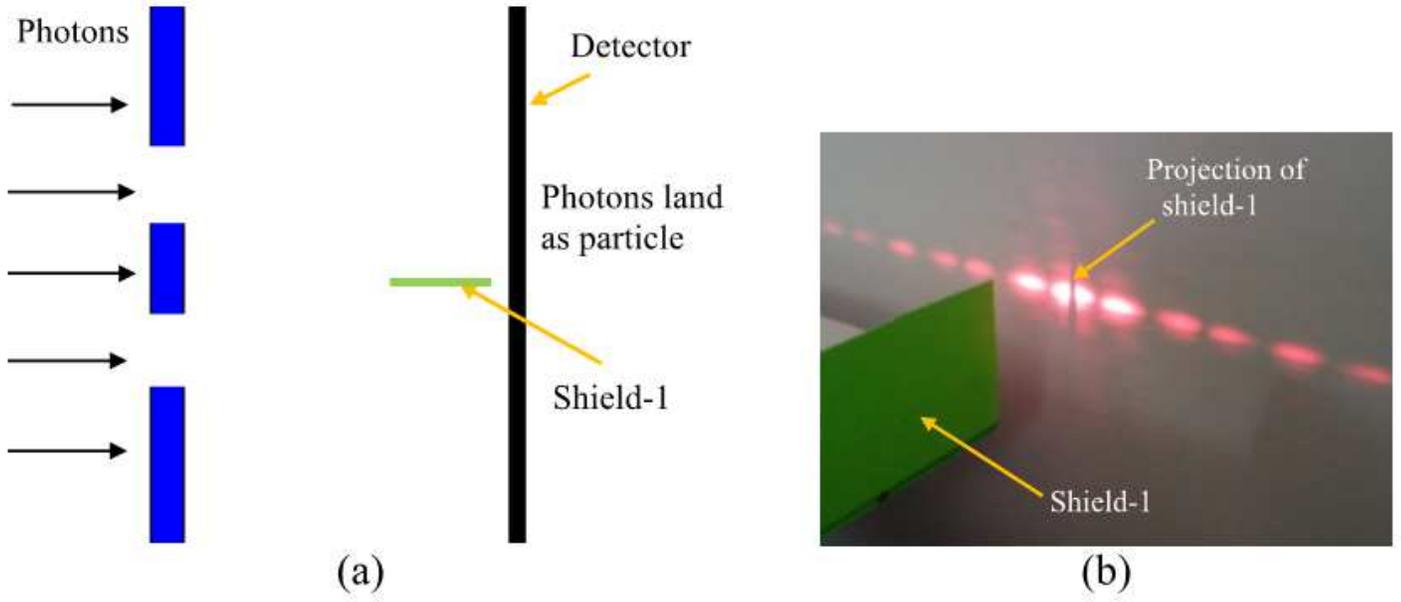


Figure 8

### Testing Postulate-2 with Single Shield

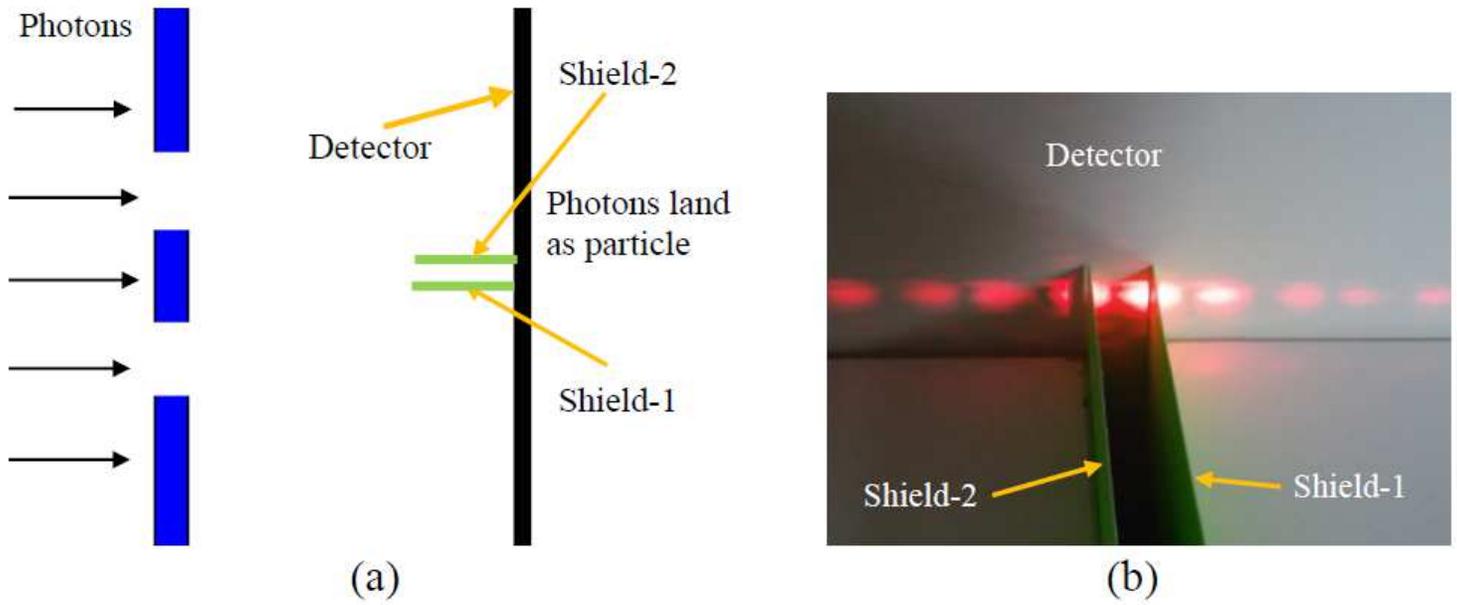


Figure 9

### Testing Postulate-2 with Two Shield (I)

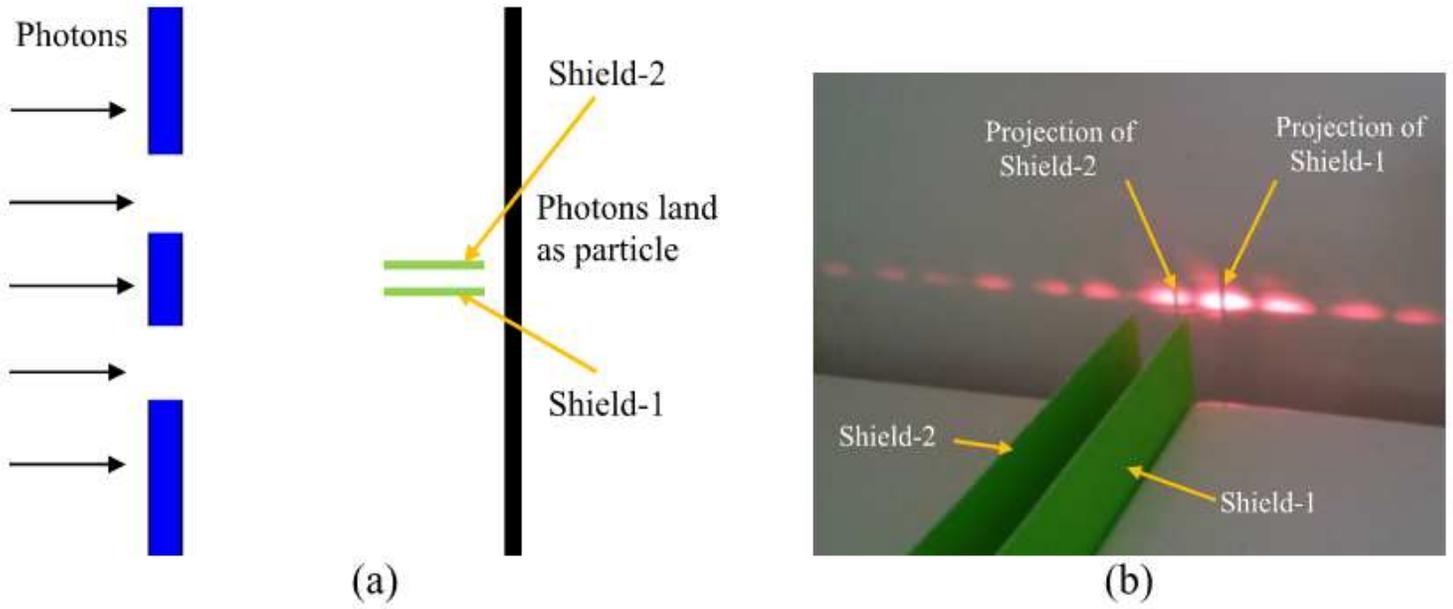


Figure 10

Testing Postulate-2 with Two Shields

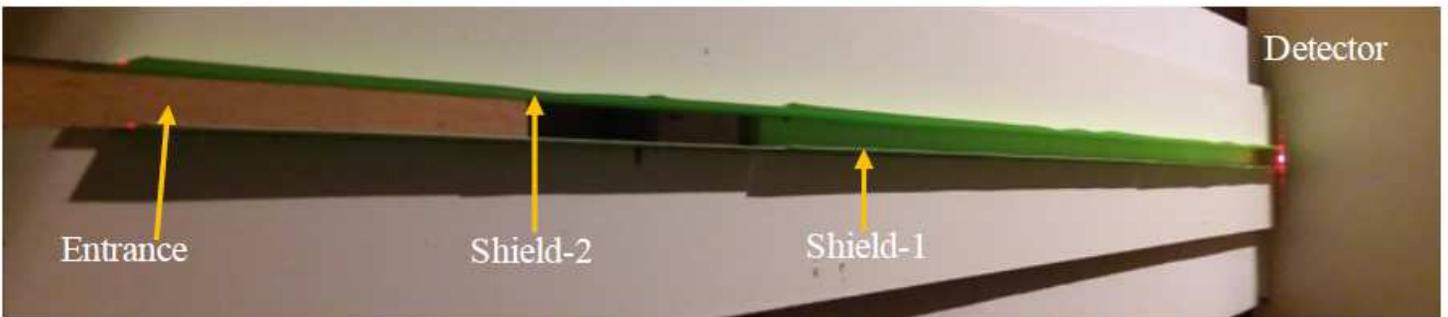


Figure 11

Testing Postulate-2: Two 70 Inches Shields (IV)

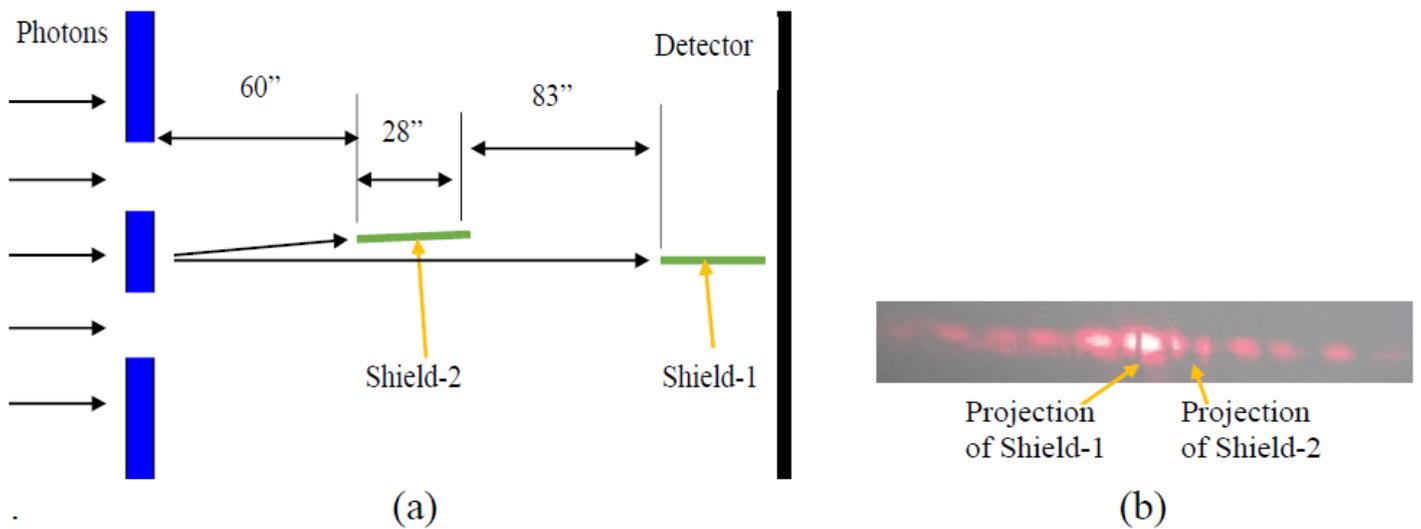


Figure 12

Testing Postulate-2 with Two Shields (V)

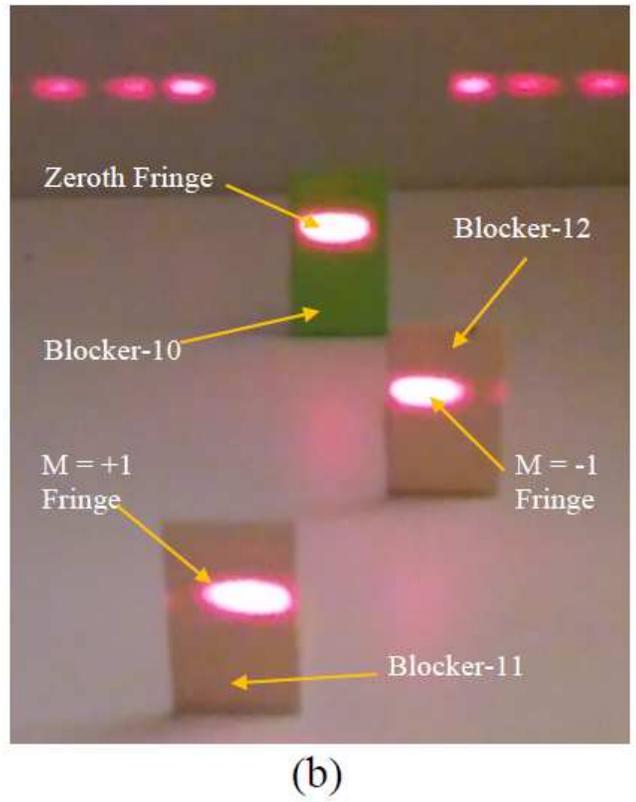
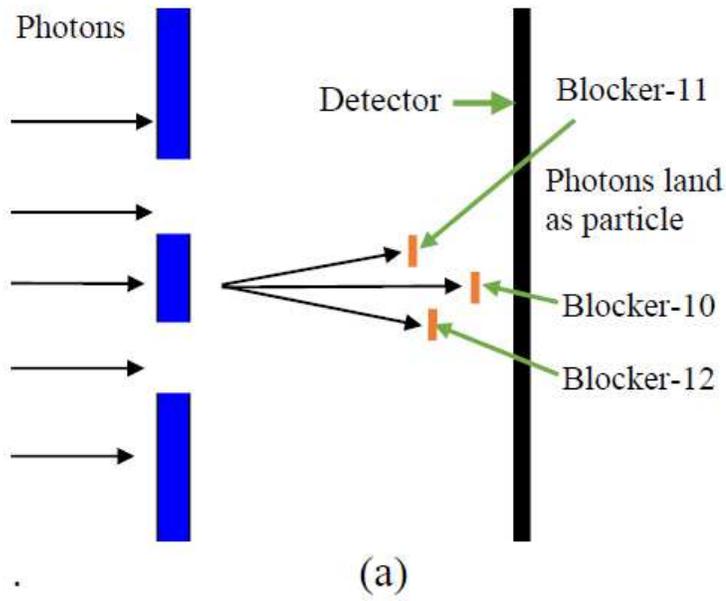
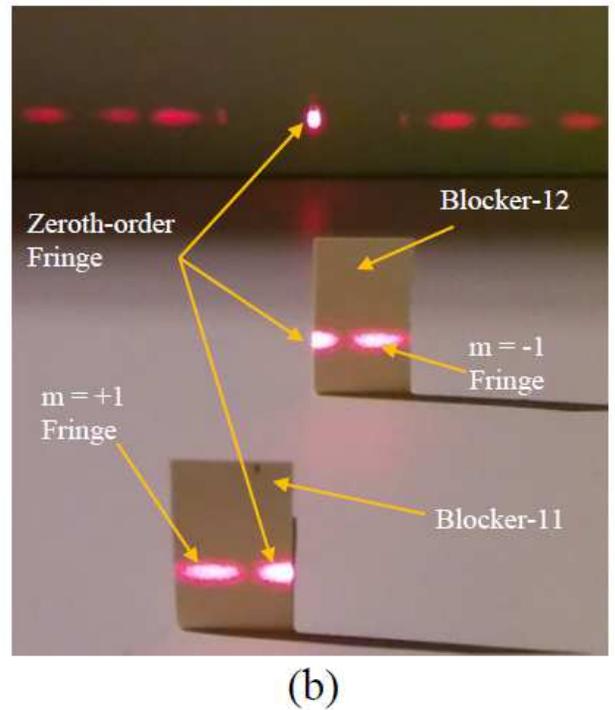
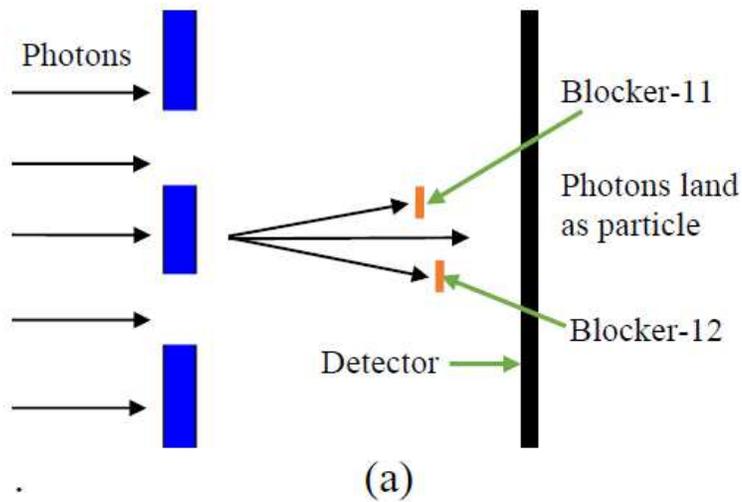


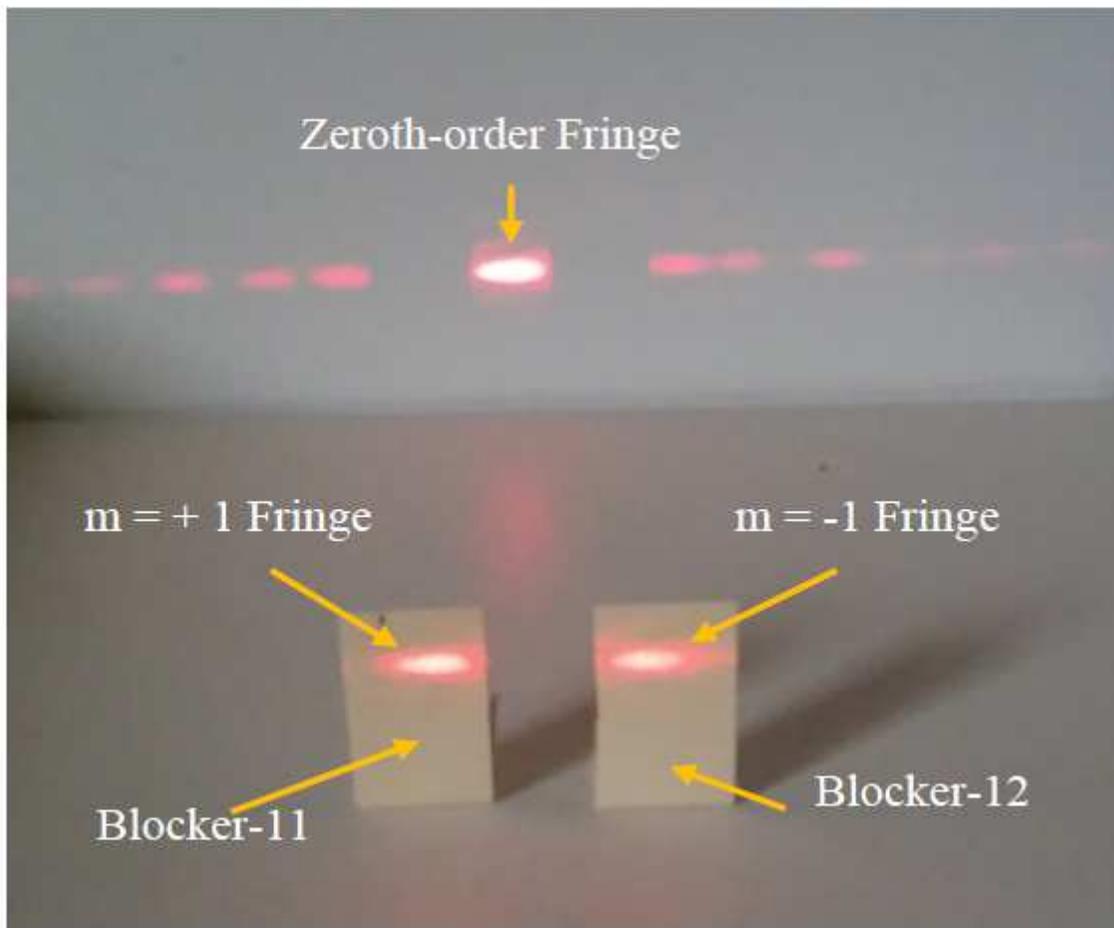
Figure 13

Schematic Setup and Observation



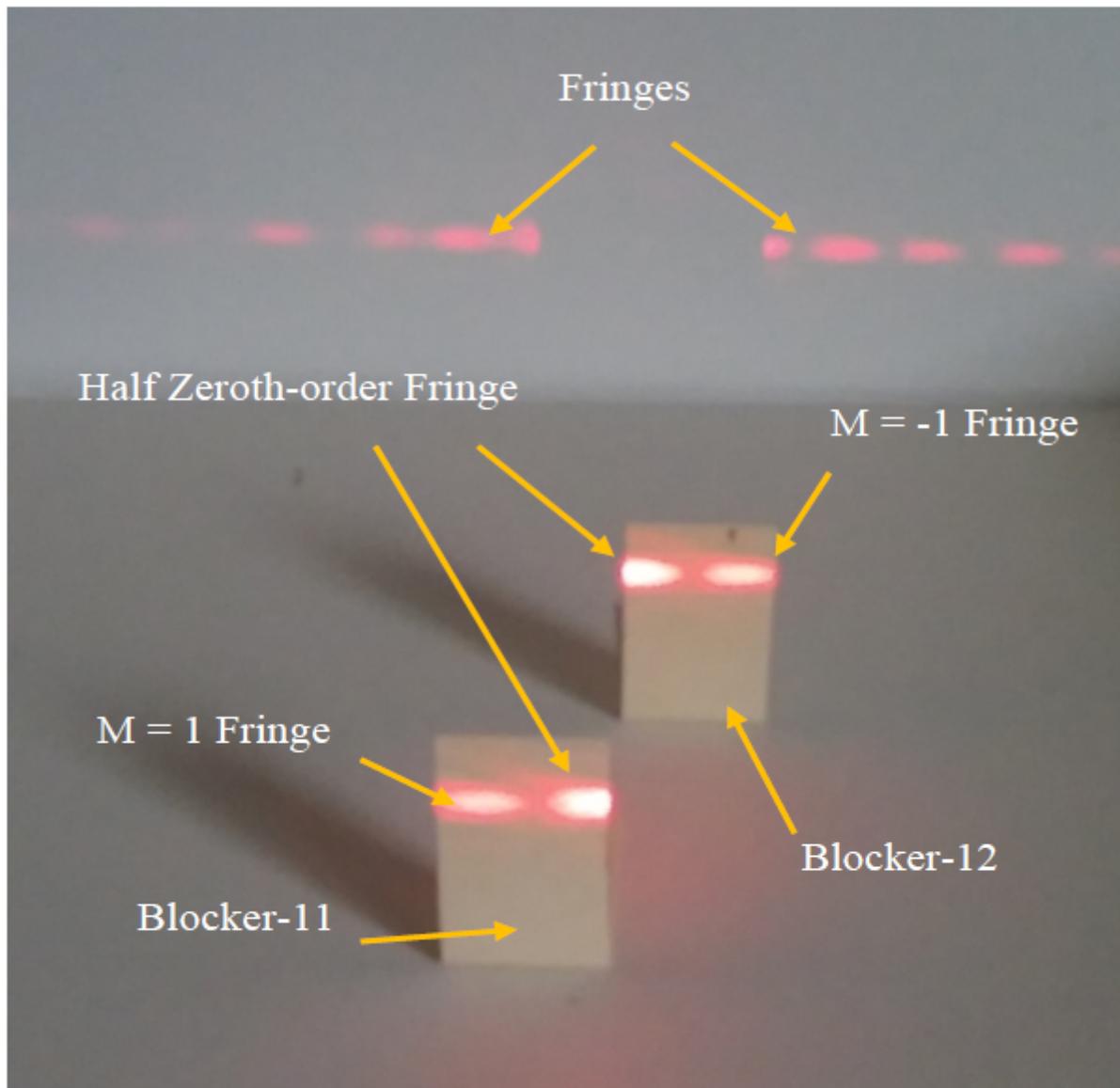
**Figure 14**

Fringes Formed Independently and Partially



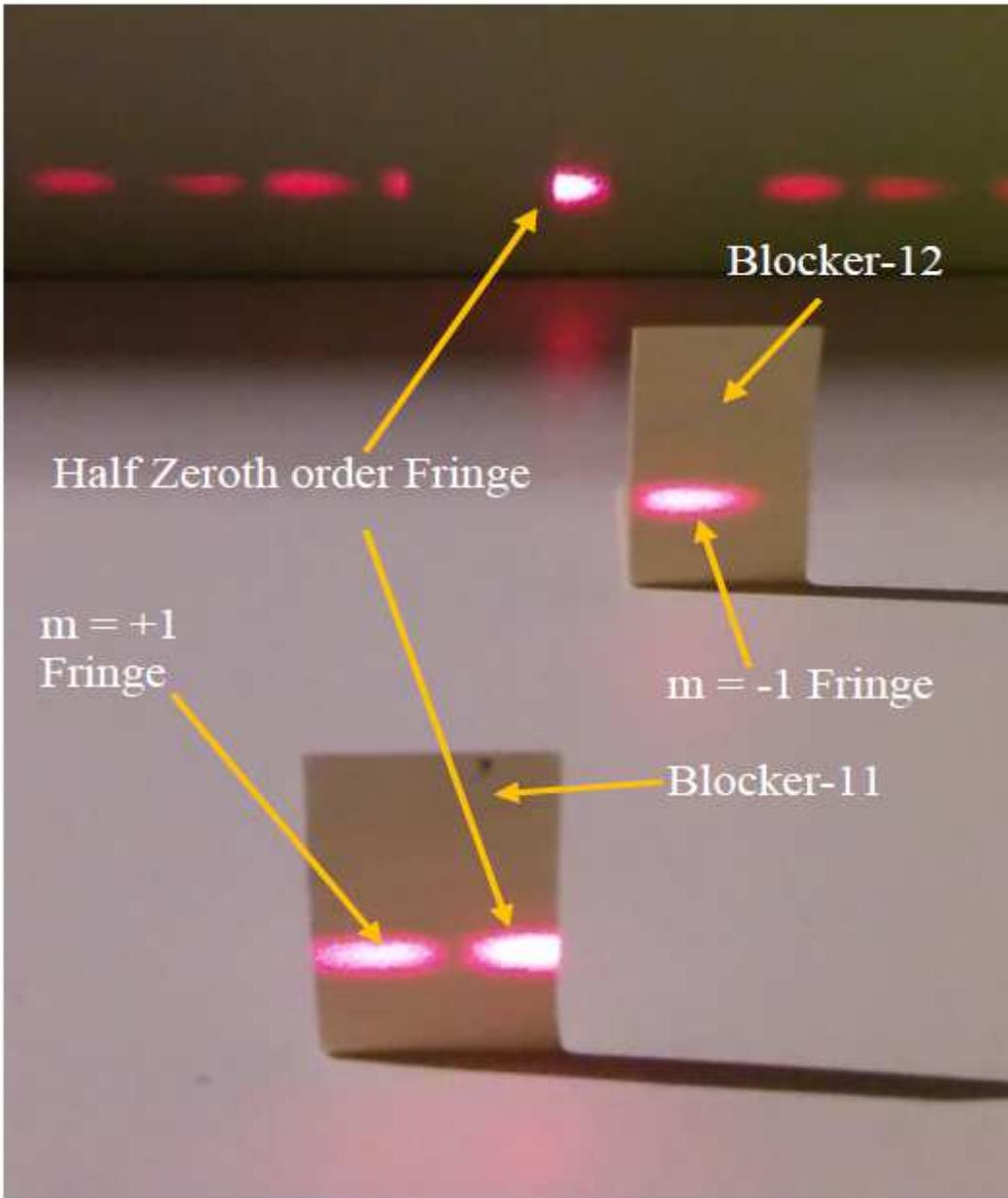
**Figure 15**

Fringes Formed Independently



**Figure 16**

Fringes Formed Independently and partially



**Figure 17**

Fringes Formed Independently and partially

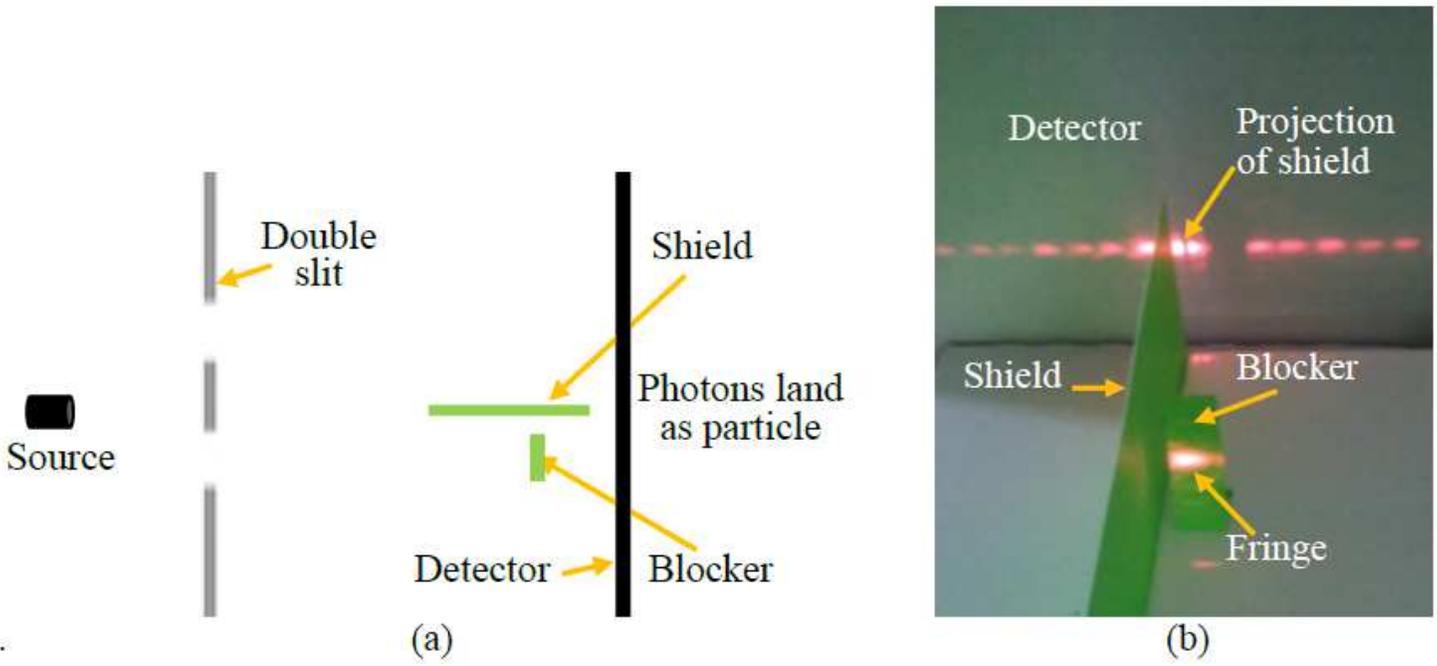


Figure 18

Testing Postulate-2 with Single Shield and Blocker

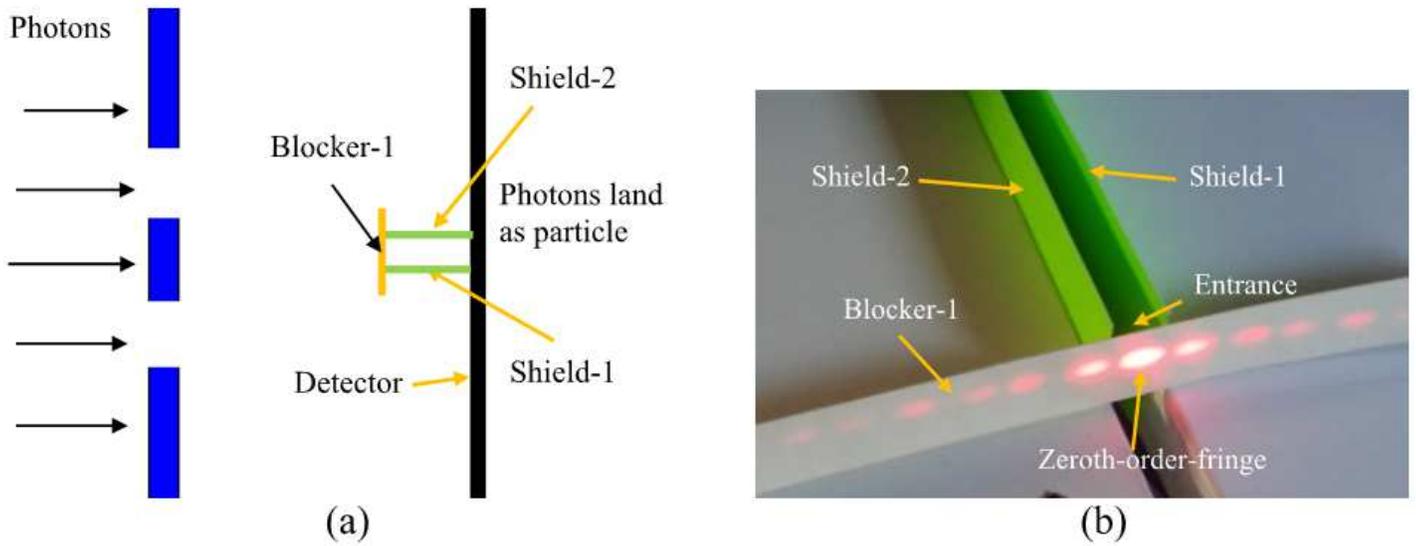
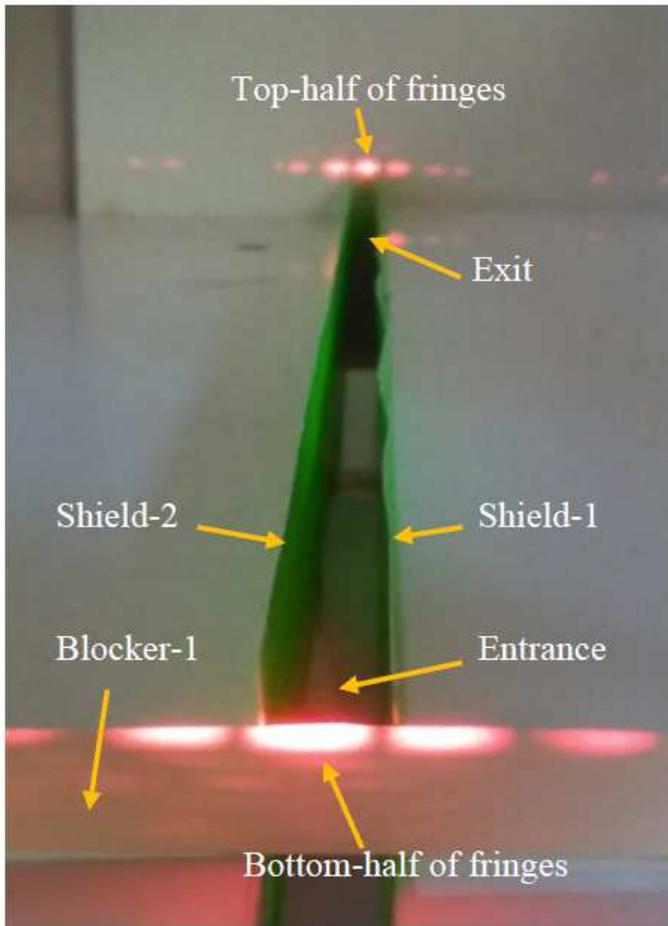
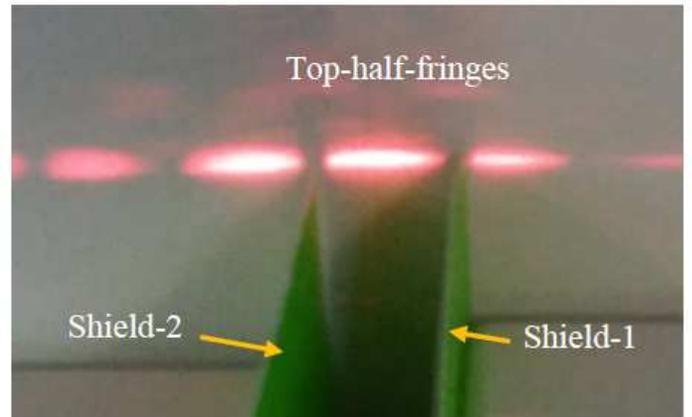


Figure 19

Shields and Blocker



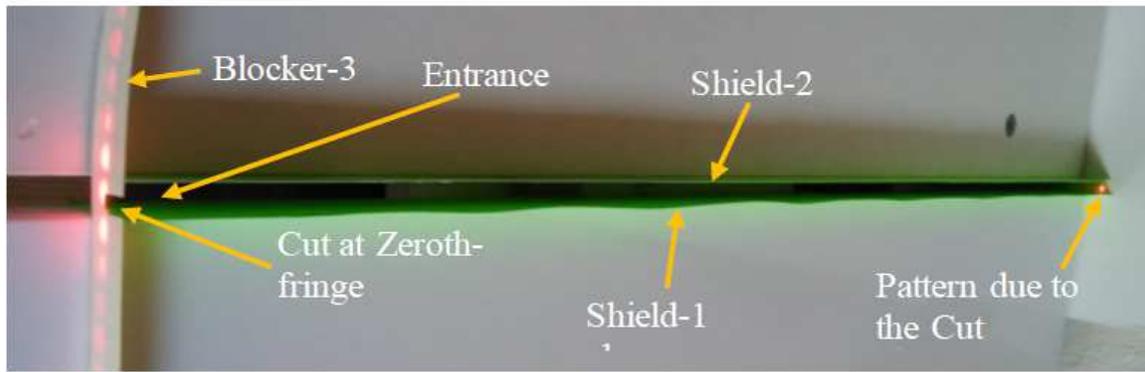
(a)



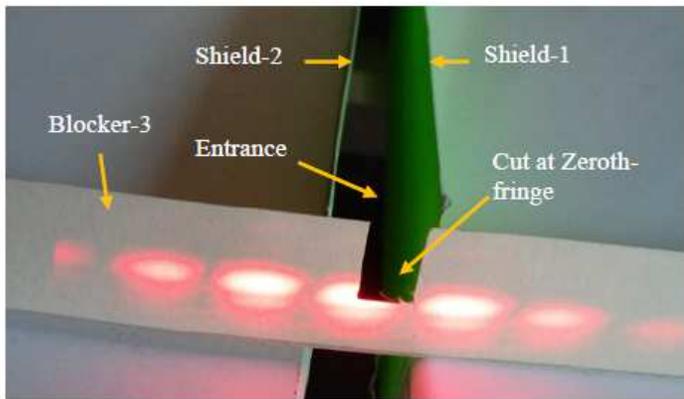
(b)

Figure 20

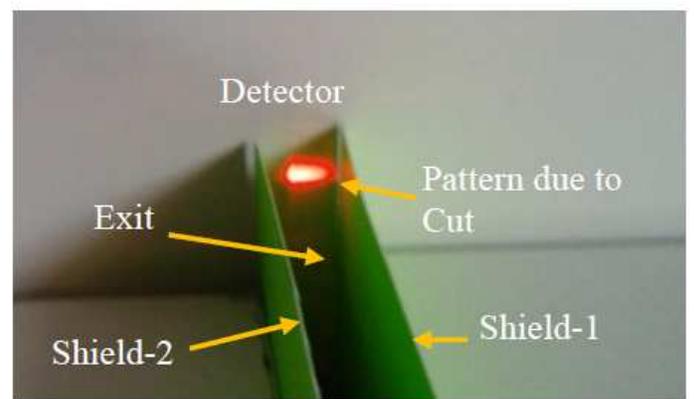
Cut Top Half of Blocker-1 and Pattern



(a)



(b)



(c)

**Figure 21**

Fringes Formed Independently and Partially

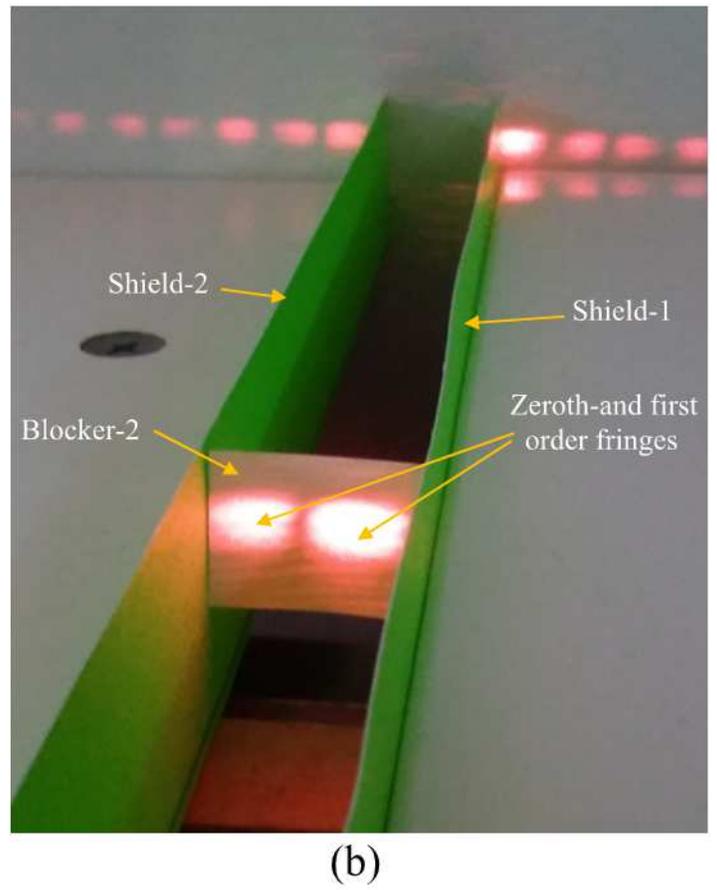
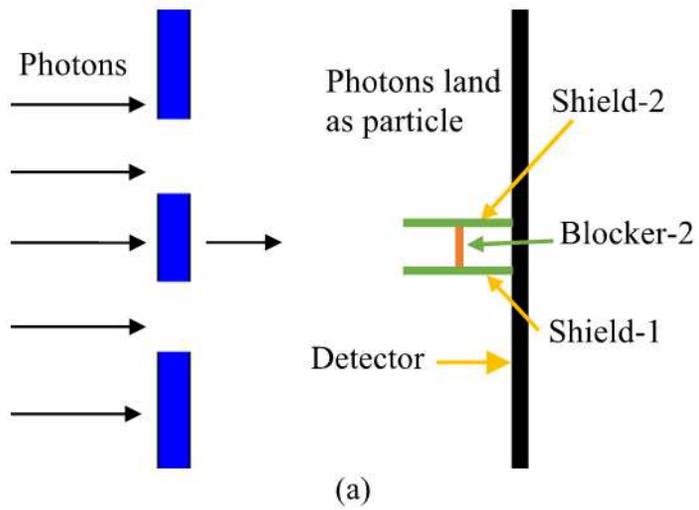


Figure 22

Blocker-2 in Channel

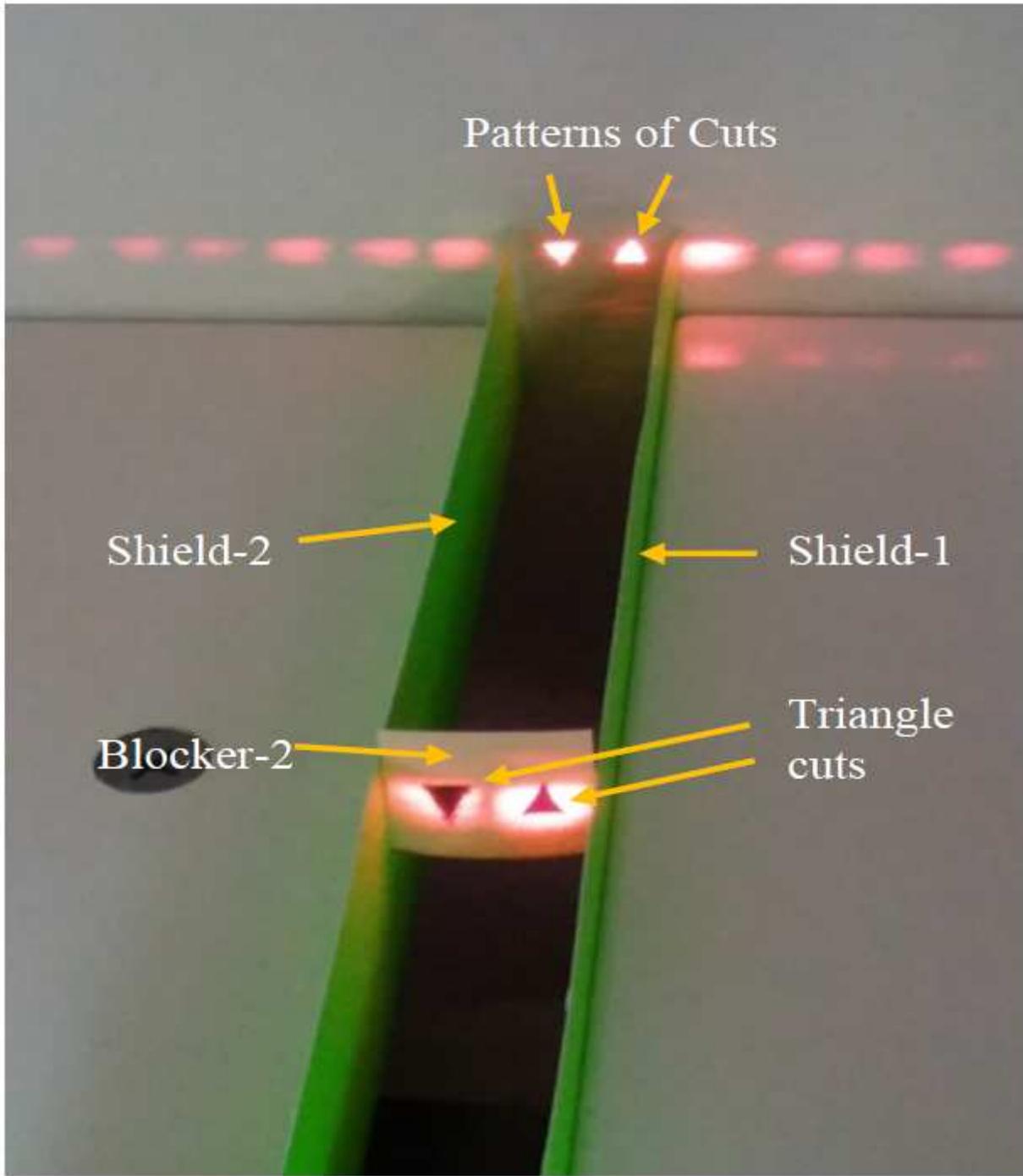


Figure 23

Blocker-2 with Two Cuts

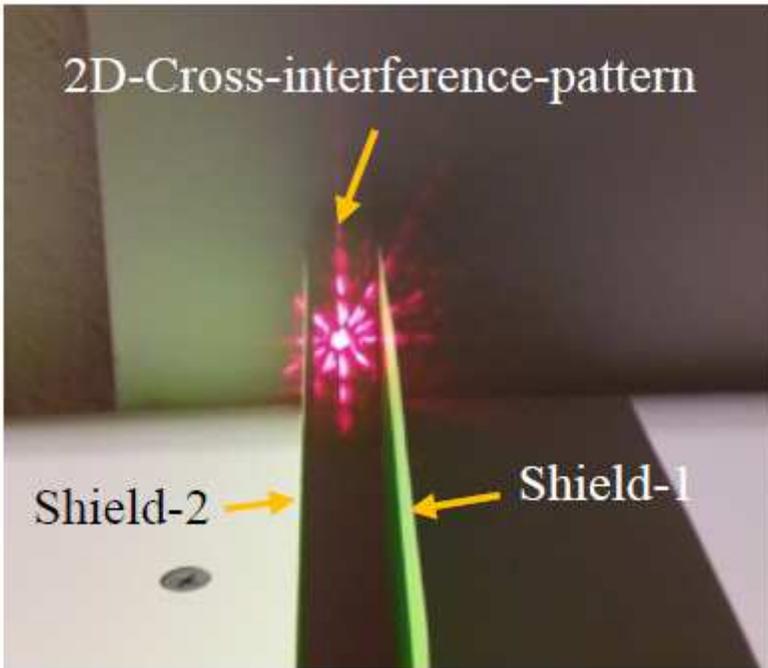


Figure 24

2D-pattern with Channel

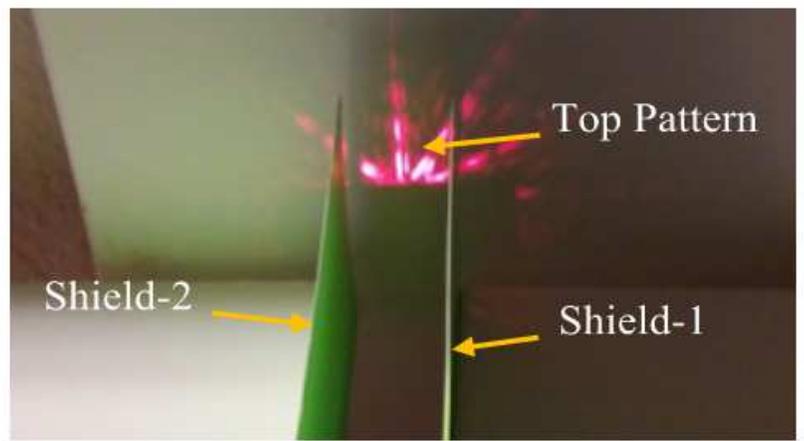
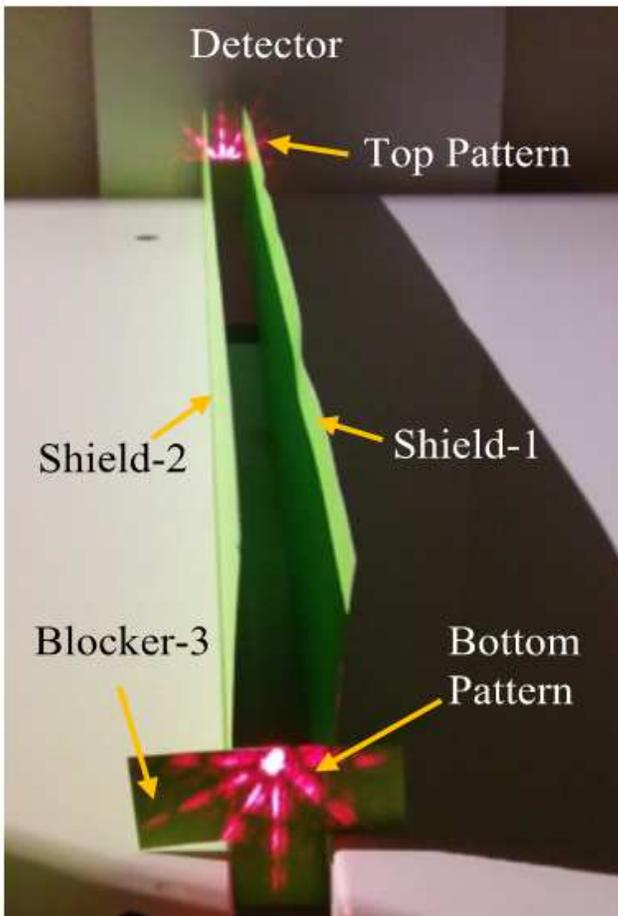
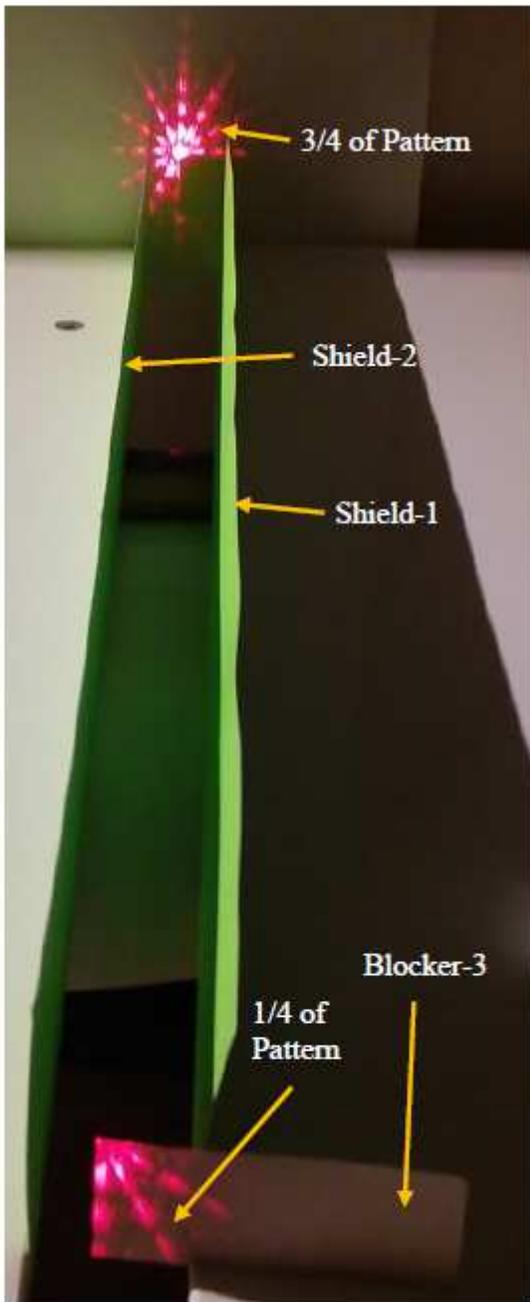
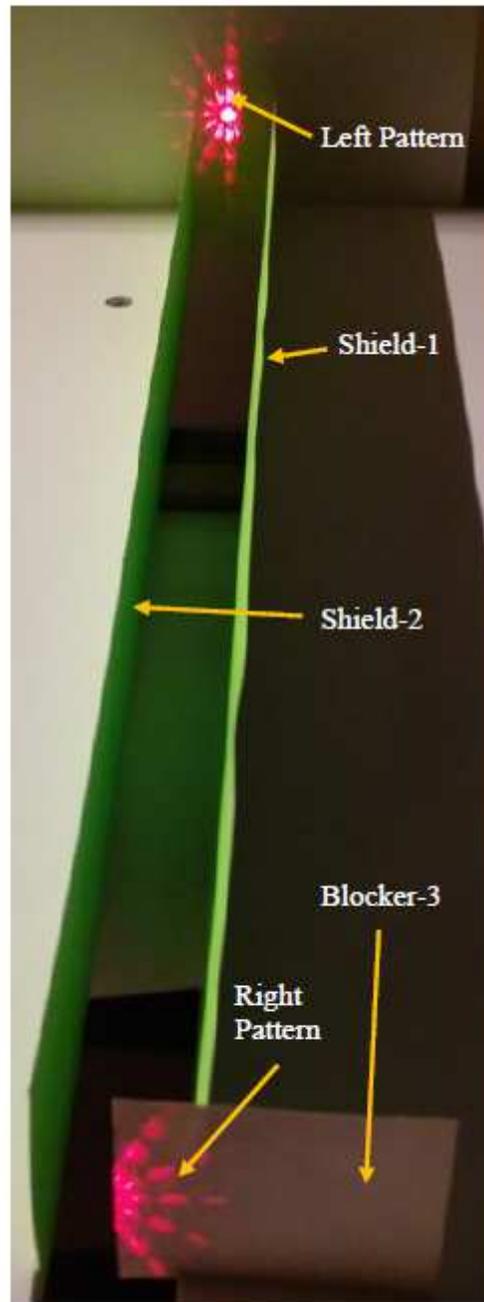


Figure 25

Testing Postulate-2 with Cross-double slit



(a)



(b)

Figure 26

Testing Postulate-2 with Cross-double slit

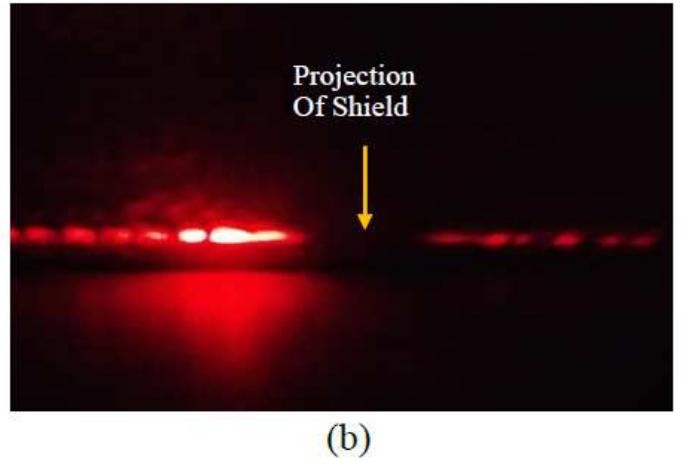
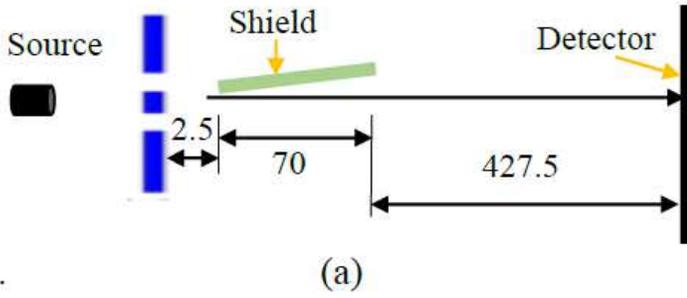


Figure 27

Schematic Setup and Observation (Unit: cm)