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SERVICES FOR SCIENCE AND EDUCATION

Double-slit, Comprehensive-Double-Slit and Irregular-Double-Slit Experiments Showing that Light is Photons and It is Photons that Produce both Non-Interference Patterns and Interference Patterns in Same Experiment: PhotoWave Phenomena and Optics-Butterfly-Effect

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ABSTRACT

Young's double slit experiments have been descripted by wave theories, i.e., before and after passing through a double slit, the light is waves. To test the wave description, we extend the double slit experiments to the comprehensive double slit experiments which are the regular double slit experiments with added either Shield, or Blocker, or Metal tube, or Photon-Chamber, or Lens. The comprehensive double slit experiments show the novel phenomena: (1) the light is particles, not waves, before and after passing through a double slit; (2) it is the particles that form both the non-interference patterns (near the double slit) and interference patterns (near/on the detector) in the same experiment; (3) the non-interference patterns gradually evolve to the interference patterns in the same experiment. We refer to the novel phenomena as "PhotoWave phenomena" which are universal. For studying the wave theory further, we show the Irregular-Double-Slit Experiments including the non-parallel-double slit, curve-double-slit, non-parallel-curve-double slit experiments. The comprehensive-double-slit and irregular-double-slit experiments provide the new phenomena for developing theoretical model to study: (1) the nature of the light; (2) the wave theories of the light; (3) the quantum theory of the light. A complete explanation should describe all of the comprehensive double slit and irregular-double-slit experiments consistently, which is a challenge. For this purpose, we propose a Dirac-type equation to describe the Particle pattern, Transition pattern and interference pattern produced by photons in a double slit experiment.

INTRODUCTION

The interference pattern of the double slit experiment is one of basic phenomena in the study of the nature of the light, and basically two concepts: particle and waves (optical wave, Electromagnetic (EM) waves and probability waves) are reached.

***) *Light is optical waves*.** In 1801, Young performed the double slit experiment, observed the *interference pattern*, and proposed that the interference pattern could only be produced if the light was waves. The wave explanation of Young's double slit experiment was not immediately accepted by people who believed that the light propagated as particles [1]. However, they did not propose/perform experiments to support the particle theory.

***) *Light is EM waves*.** In 1860s, Maxwell predicted the EM waves. The speed of the EM waves is very close to that of the light. This was considered as evidence of that the light is EM waves.

***) *Light is particles*.** From 1887 to 1905, Hertz, Thomson, Lenard, and Einstein discovered/interpreted the "Photoelectric effect", which shown the light is photons.

) *Matter waves. In 1924, de Broglie noticed that the light behaves as both the waves and particles. Then, he extended the dual concept of the light to the matter, proposed the "de Broglie matter wave", and the wave-particle duality. In January 1926, the "matter wave" led Schrodinger to propose the "Schrodinger wave equation" to describe the matter-wave, the basis equation of the quantum mechanics.

***) *Probability wave*.** In December 1926, Born explaned the wavefunction as that its square is the probability of finding a particle at a given position [2].

***) *Feynman Mistery of double slit experiment*.** In 1956, Feynman called the double slit experiment "a phenomenon … has in it the heart of quantum mechanics. In reality, it contains the only mystery. We cannot make the mystery go away by 'explaining' how it works" [3].

***) *Penrose's statement*.** In 2022, Penrose in an interview stated: "this is not something that people normally even recognize as a problem I mean they do but they shove it under the carpet which is known as the collapse of the wave function. Now you see current quantum mechanics strictly speaking is an inconsistent theory that is rather brutal way of saying what Einstein and Schrodinger and even Dirac said that quantum mechanics is incomplete" [4].

In this article, to study the nature of the light in the double slit experiments, we propose to utilize either Shield, or Blocker, or Metal tube, or Photon-Chamber, or the convex lens in the experiments, referred to such experiments as the *comprehensive double slit experiments*. We show: (1) the Shield and Blocker do not disturb the interference-patterns. (2) the Metal tube does not disturb the interference-patterns. (3) The Photon Chambers placed between the light source and the detector, show the particle nature of the light. (4) the lens in the double slit experiments shows the pattern evolution, i.e., the non-interference pattern near the double slit evolving to the orthogonal interference pattern near/on the detector, which reveal the fundamental particle nature of the light.

The comprehensive double slit experiments show for the first time the *PhotoWave phenomena*, namely, the light is photons and it is photons that form both the non-wave-pattern and the wave-pattern in the same wave experiment. The PhotoWave phenomena are fundamentally significant in the further development of optics/physics. To test the theories of the double slit experiment further, we propose/study the non-parallel-double slit, the curve-double slit, and the non-parallel-curve-double slit experiments. The above experiments also show the PhotoWave phenomena.

To interpret consistently/completely the PhotoWave phenomena is a challenge. For this purpose, we propose a Dirac-type equation to describe the Particle pattern, Transition pattern and interference pattern produced by photons in a double slit experiment.

ZONES AND POSTULATES

Four Zones

Let us divide the space between the laser source and the screen/detector into four Zones (Figure 1). Each Zone is defined by the corresponding patterns in the Zone. There are is no clear-cut between two Zones. When the pattern gradually evolves, the corresponding Zone gradually changes to the next Zone.

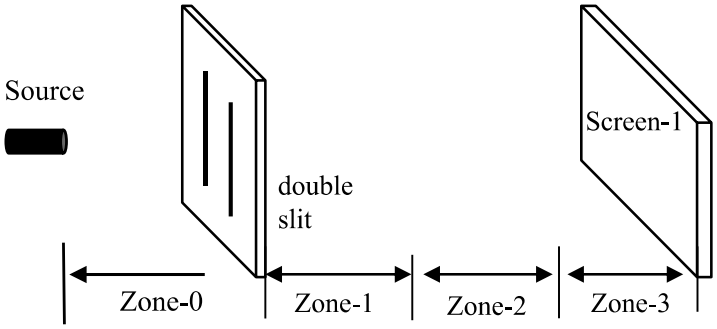


Figure 1: Four Zones

1. Zone-0: between the source and the double slit, in which the pattern is non-wave and thus, the light is particles;
2. Zone-1: near the double slit, in which the patterns are *non-interference* and thus, the light is particles; referred to the patterns as ***Particle patterns***;
3. Zone-2: between zone-1 and zone-3, in which the patterns are *non-interference* and thus, the light is particles; referred to the patterns as ***Transition patterns***; in Zone-2 Particle patterns in Zone-1 gradually evolve to the Interference patterns in Zone-3.
4. Zone-3: near the screen, in which the patterns are ***Interference patterns***;
5. Surface of the screen: on which the light lands as particles and it is the particles that distribute as interference pattern.

Postulate on Light

(1) "Classical Postulate on light": ***the light is waves before and after passing through a double slit***. To my knowledge, there is no experiment testing it. The existing experiments only show that the light distributes as the interference pattern ***on the detector***, but not between the double slit and detector, i.e., Zone-1, Zone-2 and Zone-3, and not between the light source and double slit, i.e., Zone-0. Now, we propose a New Postulate on light and then, experimentally test/confirm it.

(2) "New Postulate on light": *Light is particles before and after passing through a double slit, and landing on a detector.* One of the conclusions of the "New Postulate on light" is that the nature of the Light in a double slit experiment does not change. Namely, if an experiment confirms that the light is particles in one of Zones, then, the light is particles in all of Zones.

"New Postulate on light" completely alters the understanding of the nature of the light, especially the nature of the light in the double slit experiment.

Example: If the light shows particle nature in Zone-1, then the light is photons in all four Zones and on the detector, i.e., the light has the same particle nature before and after passing through the double slit.

Note: "New Postulate on light" avoids the introduction of the concept of the "*Collapse of Wave Functions*" and thus, supporting Penrose's statement.

(3) PhotoWave phenomena

If it is confirmed that the light is particles in one Zone and then, the light is particles in all Zones. And it is photons that produce both the non-interference/non-diffraction patterns and the interference/diffraction patterns, referred to it as the PhotoWave phenomena.

Postulate on Lens

In the classical double slit experiments, it was assumed that the function of the convex lens is to *bring light rays to a focal point P on the screen.* We will show that the pattern changes with the distance from the diaphragm. To study the evolution of the patterns, the lens moves between the diaphragm and the detector and thus, the patterns arriving at the input surface of the lens change. The light patterns arriving at the input surface of the lens are position-dependence. Based on above consideration, we suggest the Postulate on lens.

Postulate on Lens:

(1) the lens enlarges the image that arrives at the input surface; (2) The lens breaks the evolution of the patterns; (3) The lens does not change the behavior of the input pattern.

Example: After passing a lens, the patterns keep the same nature: e.g., (a) if the input pattern is Particle pattern, the output pattern is still Particle pattern, and vice versa; (b) if the input pattern is Transition pattern, the output pattern is still Transition pattern, and vice versa; (c) if the input pattern is Interference pattern, the output pattern is still Interference pattern, and vice versa.

COMPREHENSIVE DOUBLE SLIT EXPERIMENTS: LIGHT IS PHOTONS THAT PRODUCE INTERFERENCE PATTERN

In Section 3, we confirm experimentally the "New Postulate on light".

Light Is Particles Before Passing Through Double Slit

Double Slit experiment with Photon Chamber:

Now, let us experimentally show that the laser beam is particles before passing through a double slit, i.e., in Zone-0, the light is particles.

Experiment-1 (Figure 2): Light is photons before passing through double slit:

- **Experimental setup** (Figure 2a): Placing a Photon Chamber between the laser and the double slit (Zone-0).
- **Observation** (Figure 2b): The Photon Chamber shows the photon track (pattern) which shows that the light is photons, not waves.
- **Conclusion:** the light is photons before passing through the double slit.

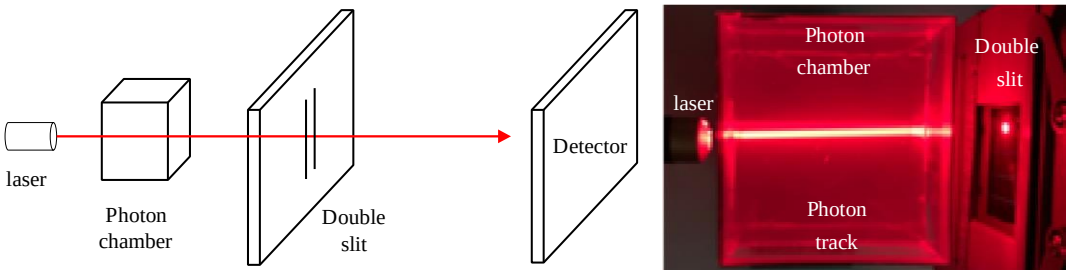


Figure 2: Experimental setup and pattern showing Light is particles before passing through double slit

Double Slit experiment with Beam Splitter (BS):

We will utilize the following rule.

- **Rule: A Beam Splitter (BS) does not change the behavior of the light.**
- **Example**: when a light beam reflected by a BS behaves as particles, then the input light beam behaves as particles, while the transmitted light beam behaves as particles.

Experiment-2 (Figure 3)

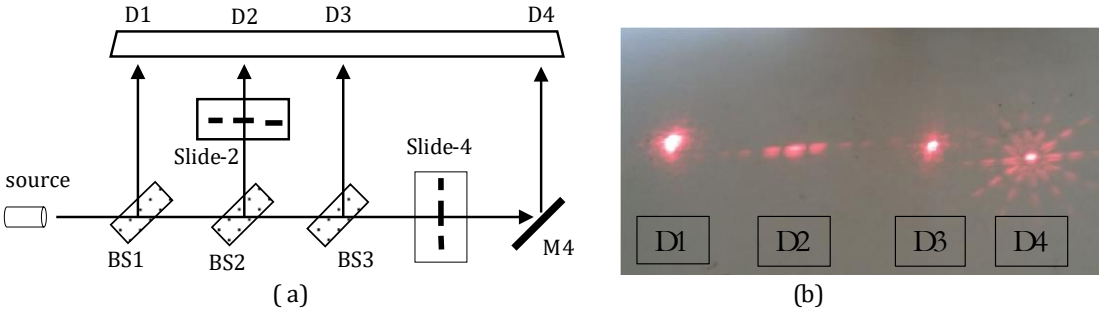
- **Experimental setup**: A laser beam partially reflected by BS1 arrives at D1 on detector, and partially transmitted though BS1 and reflected by Mirror-1 (M1) arrives at D2 on detector. A larger screen is used (Figure 3a).

Figure 3: Light is particles before passing through double slit

- **Observation** (Figure 3b): both D1 and D2 show the images of the source.
- **Conclusion:** The light detected on both D1 and D2 have the same particle nature. The particle nature of the light is not changed by either being reflected by BS or passing through BS.

Experiment-3 (Figure 4): Light is photons before passing through double slit

- **Experimental setup** (Figure 4a): the light passing through BS1/BS2/BS3 and slide-4 arrives at D4; the light reflected by BS1 arrives at D1; the light reflected by BS2 passes through slide-2 and arrives at D2; the light reflected by BS3 arrives at D3.
- **Observations** (Figure 4b): D1 shows the image of the source, which indicates that the light is particle before passing the slide-2 and slide-4; D2 shows the wave distribution; D3 shows the image of the source, which indicates that the light is particle before passing the slide-4; D4 shows the wave distribution. Slide-2 ia a double slit, while Slide-4 is a cross-double slit.



(a) (b)

Figure 4. Light is particles before passing through slides of double slit

- **Conclusion**:
  - Based on Rule, since the light reflected by BS1 and BS3 behaves as particles, thus, before arriving at slide-2 and slide-4, the light is particles respectively.
  - Slide-2 and slide-4 convert light's particle behavior (before arriving) to wave distribution (after passing through) respectively. The slide changes the behavior of photons only when the light pass through it, but not the behavior before passing it. The wave distribution doesn't indicate that the light is wave.
  - The particle nature and wave distribution coexist in the same experiment.

Light Is Photons After Passing Through Double Slit
Double Slit Experiment with Photon-Chamber:
Experiment-4 (Figure 5): Photon Chambers show the top view of patterns.

- **Experimental setup** (Figure 5a): Photon chamber-1, Photon chamber-2 and Photon chamber-3 placed in Zone-1, Zone-2 and Zone-3 respectively. Each photon chamber is 50x50 mm.

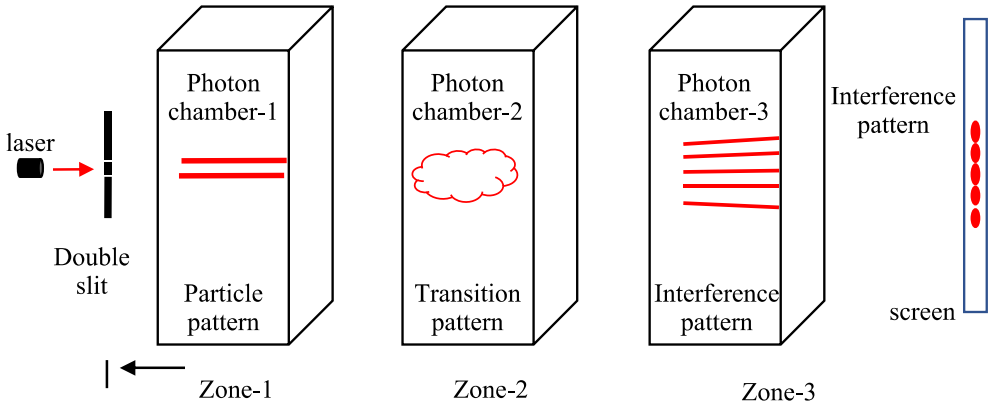


Figure 5a: Experimental setup

Let us define Particle pattern, Transition pattern and Interference pattern:

1) **Particle pattern** (Figure 5b): When classical particles going through a double slit, they will form the pattern with the shape of the double slit, referred to it as Particle pattern. A double slit produces the same shape patterns in Zone-1 as two photon tracks in Figure 5b. Thus, we define the pattern of two photon tracks as "Particle pattern" that indicates that the light behaves as particles in Zone-1.

2) **Transition pattern** (Figure 5c): Transition patterns are in between the Particle patterns in Zone-1 and the Interference patterns in Zone-3. When Particle patterns gradually evolve to Interference patterns, they are neither Particle pattern nor Interference pattern and thus, the light behaves not as a wave in Zone-2. We call them the "Transition patterns". The transition pattern is the non-interference pattern.
3) **Interference pattern** (Figure 5d): Figure 5d shows the interference pattern, referred to it as "PhotoWave phenomenon".

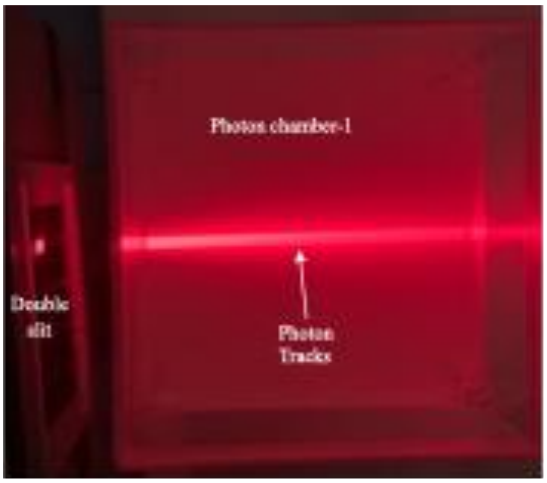


Figure 5b: Particle patterns in Zone-1

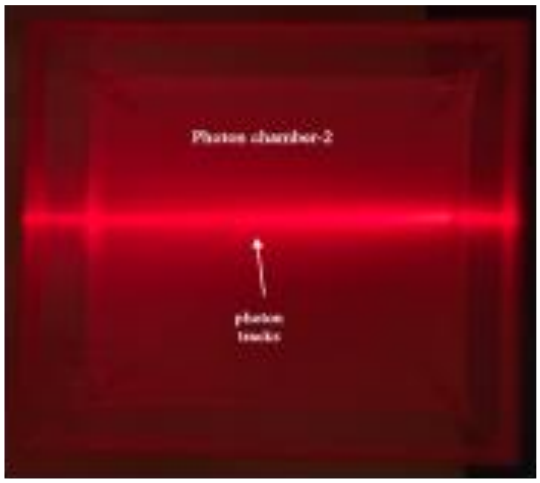


Figure 5c: Transition pattern in Zone-2

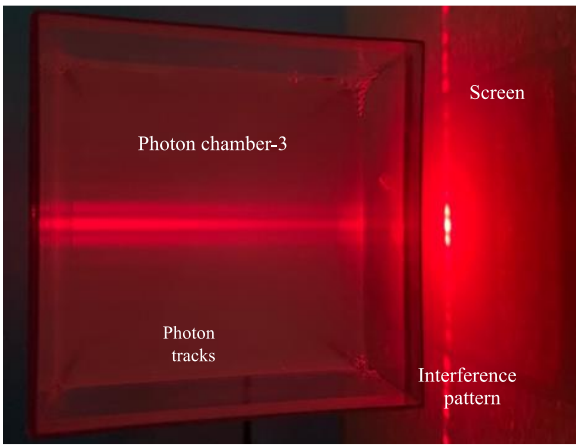


Figure 5d: Interference pattern in Zone-3

- **Observation**: Photon chamber-1 shows the top view of the photon tracks distributing as Particle pattern. Photon chamber-2 shows the top view of the photon tracks distributing as Transition pattern. Photon chamber-3 shows the top view of the photon tracks distributing as Interference pattern.
- **Conclusion**: Particle patterns and Transition patterns indicate that the light is particles, not waves, after passing through the double slit. Figure 5d shows that the light is photons and it is photons that form the interference pattern. Thus, according to the "New Postulate on light", the light is photons in all four Zones. To explain "photons distribute as wave" is a challenge.

- **Note:** the boundaries between Zone-1 and Zone-2, and between Zone-2 and Zone-3 are not clear cut. Patterns in one Zone gradually evolve to different Patterns in another Zone.

Double Slit Experiment with Shields:

Experiment-5 (Figure 6): Light is photons after passing through double slit: two Shields

- **Experimental setup**: Two shields form a narrow channel. Shield-1 and Shield-2 are 70 inches long, 1.5 inch wide, and 0.3 mm thick. Both Shield-1/Shield-2 contact the detector.

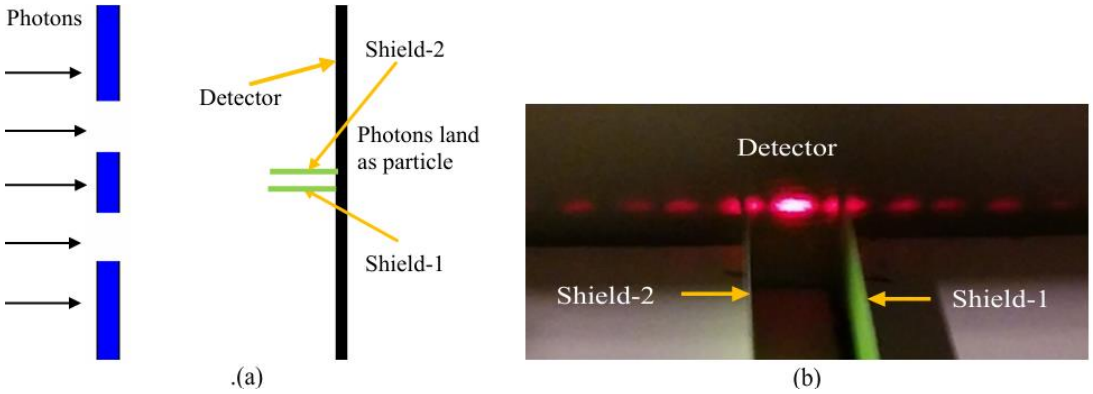


Figure 6: Double slit experiment with two Shields

- **Observation** (Figure 6b): We observe the interference pattern that is the same as there were no shield-1 and shield-2. The existence of two parallel Shields has no effect on the "interference" pattern, which indicates that the light is photons that producing interference pattern on the detector.
- **Conclusion**: Only the light as particles can (1) pass through the narrow channel; (2) strike at the positions of the zeroth-order fringe and two first-order fringes on the detector; (3) form two projections; and (4) do not disturb the existing interference pattern.

Double Slit Experiment with Blockers:

Experiment-6: Light is photons after passing through double slit: Blocker.

- **Experimental Setup** (Figure 7): Blocker-11 and blocker-12 are placed along the normal vector of the surface of the detector and separated by 4 inches.
- **Observation** (Figure 7): Two blockers are arranged such that portions of the zeroth-order fringe are formed on the detector, blocker-11 and blocker-12. 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.
- **Conclusion:** Experiment-6 show that_Fringes are formed independently and partially, which would be expected only if the light is photons in Z-3 near the detector. Some of photons form fringes on blockers, while some of photons form the rest interference pattern on the detector. "New Postulate on light" is experimentally confirmed.

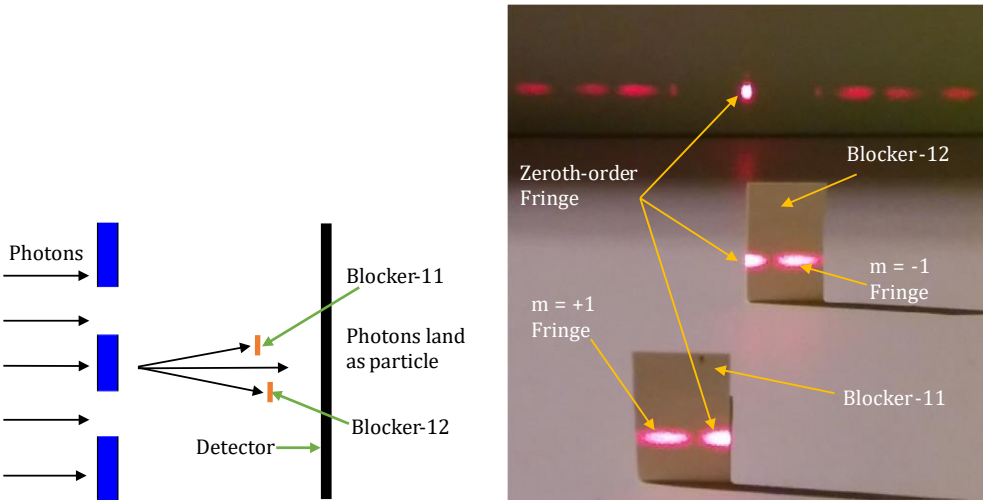


Figure 7: Fringes Formed Independently and Partially

Double Slit Experiment with Both Shields and Blockers:
Now let us show the effects of combinations of Shields and Blockers.

Experiment-7: Testing "New Postulation on light": combination of Shields and Blocker in two setups.

- **Experimental Setup-1** (Figure 8): One end of the channel of shield-1/shield-2 contact the detector. Place blocker-1 at the other end of the channel, where we denote it as Entrance.

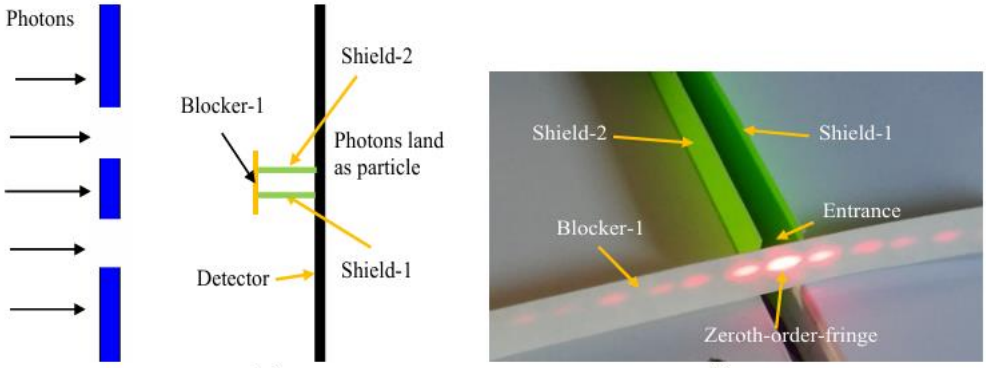


Figure 8a and 8b: Testing New Postulate on light with Shields and Blocker

- **Observation** (Figure 8b): The interference pattern is formed on blocker-1.

- **Experimental Setup-2** (Figure 8c): Cutting off the top portion of blocker-1.
- **Observation** (Figure 8c and 8d): The bottom half of the fringes still appears on blocker-1, while the top half of the fringes appears on the detector. Namely each fringe is formed partially. Shields have no effect on the interference pattern at all.

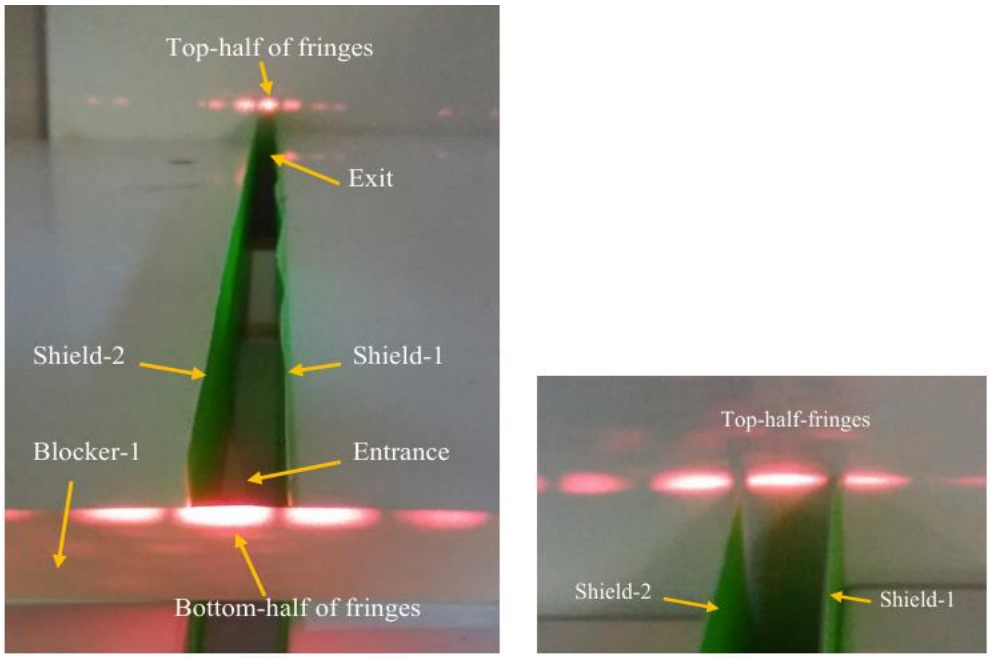


Figure 8c and 8d Testing New Postulate on light: Cut Top Half of Blocker-1

Experiment-8 (Figure 9): We perform this experiment in two setups.

- **Experiment Setup-1** (Figure 9a): Insert transverse blocker-2 one inch wide into the channel formed by shield-1 and shield-2.

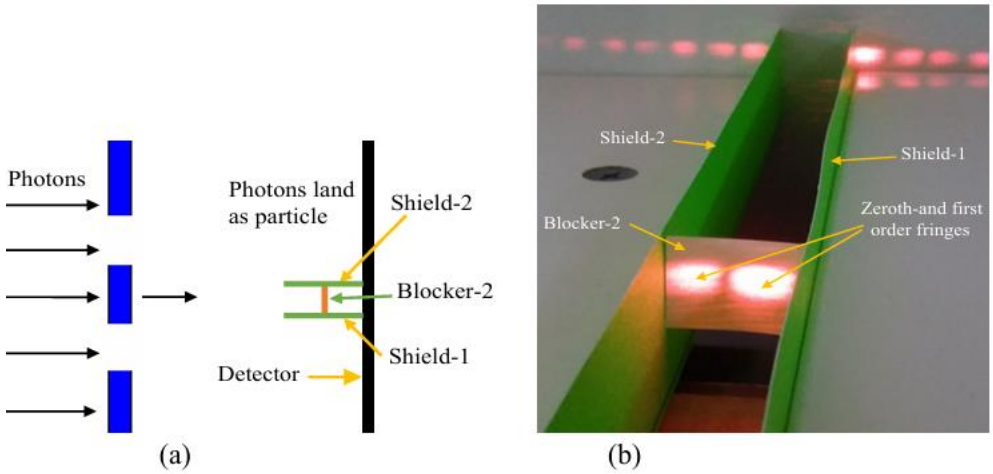
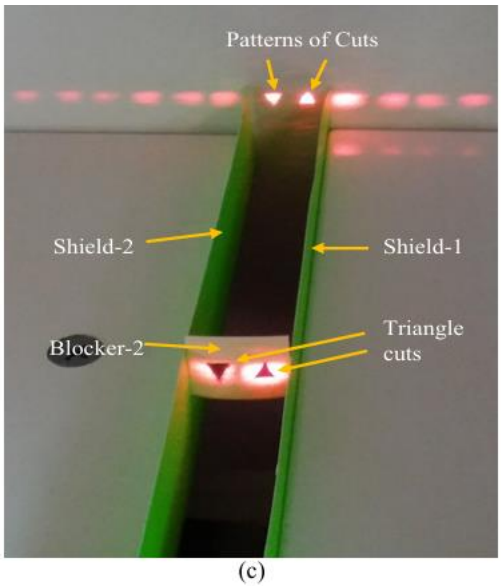


Figure 9a and 9b: Blocker-2 in Channel

- **Observation** (Figure 9b): Two fringes are formed on blocker-2, and the remaining fringes are formed on the detector. Namely, Fringes are formed independently.
- **Conclution**: Two shields have no effect on the interference pattern. This observation indicates that the light is photons.

- **Experimental Setup-2** (Figure 9c): 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.



(c)

Figure 9c: Blocker-2 with Two Cuts

- **Observation** (Figure 9c): The light passes through two triangle-shaped cuts and forms exactly the same triangle-shaped patterns on the detector.
- **Conclusion**: Figure 9c shows that the light is photons that move along straight lines.
- **Note**: the light just passes through a double slit, and is not waves. "New Postulate on light" is confirmed experimentally.
- **Pattern-Evolution: Lens:** To study the pattern evolution, we utilize a lens.

Experiment-9: Pattern evolution of Double slit experiment

- **Experimental setup**: the left of Figure 10 shows the experimental setup.

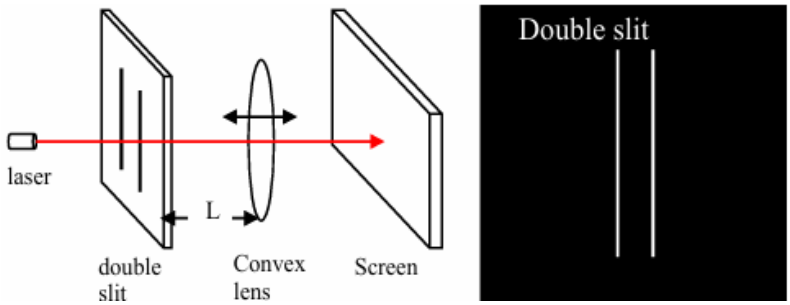


Figure 10: Experimental setup and double slits

When placing the lens at different positions L, we have the following pattern evolution.

- **Observation** (Figure 11): When L = 75 mm, the vertical pattern is the typical image of double-slit, Particle pattern. When L = 350 mm, the pattern is the typical Transition patterns. Both the Particle pattern and the Transition patterns are the non-interference patterns and thus, indicate that the light is particles after passing through the double slit (from L = 10 mm to L = 600 mm). When $L \geq 750$ mm, the patterns are the horizontal interference patterns.

- **Conclusion:** "New Postulate on light" is confirmed: the light is photons after passing through the double slit, and it is photons that form both the non-interference and the interference patterns.
- **Note**: The Particle patterns gradually evolve to the *orthogonal* interference patterns.

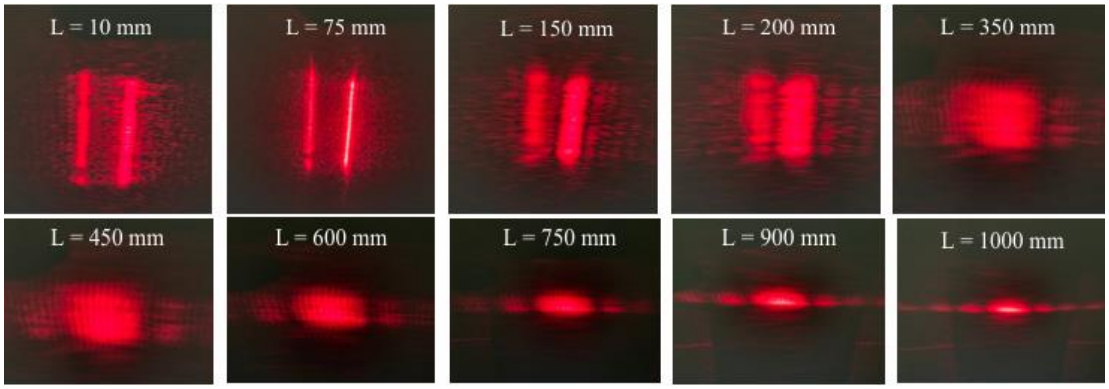


Figure 11: Evolution of patterns of double slit experiment

- **Discussion on "Collapse of Wave Functions":** In Zone-0, Zone-1, Zone-2 and on the surface of the screen, the light is particles. According to "New Postulate on light", the light in Zone-3 is photons as well. And Photons as particles distribute as wave-like pattern in Zone-3 and on the surface of the screen. According to the standard concept of the "Collapse of wave functions", in Zone-3 near the screen, the light is still waves. Then once the light lands on the surface of the screen, the wave functions of the light immediately disappeared and the light becomes photons. This process has the name "Collapse of Wave Functions". To explain the mechanism of "*Collapse of Wave Functions*" is a challenge. According to "New Postulate on light", the light is Photons in all Zones of the double slit experiment, there is no need to introduce the concept of the "Collapse of Wave Functions".

Double Slit Experiment with Conductive Metal Tube: Light is not EM Waves

Experiment-10: Testing the electromagnetic (EM) wave theory of light

- **Experimental setup** (Figure 12a): In this setup, an Aluminum (AL) rectangular tube of 0.75x1.1x48 inches is used.
- **Observation** (Figure 12): Figure 12b shows the interference pattern without AL tube. Figure 12c and 12d show the unaffected interference patterns. Figure 12c. and Figure 12d also show the projections of the two side walls of the AL tube.
- **Conclusion**: The conductive metal tube has no effect on the interference pattern, which indicates that the light is not the electromagnetic (EM) waves.

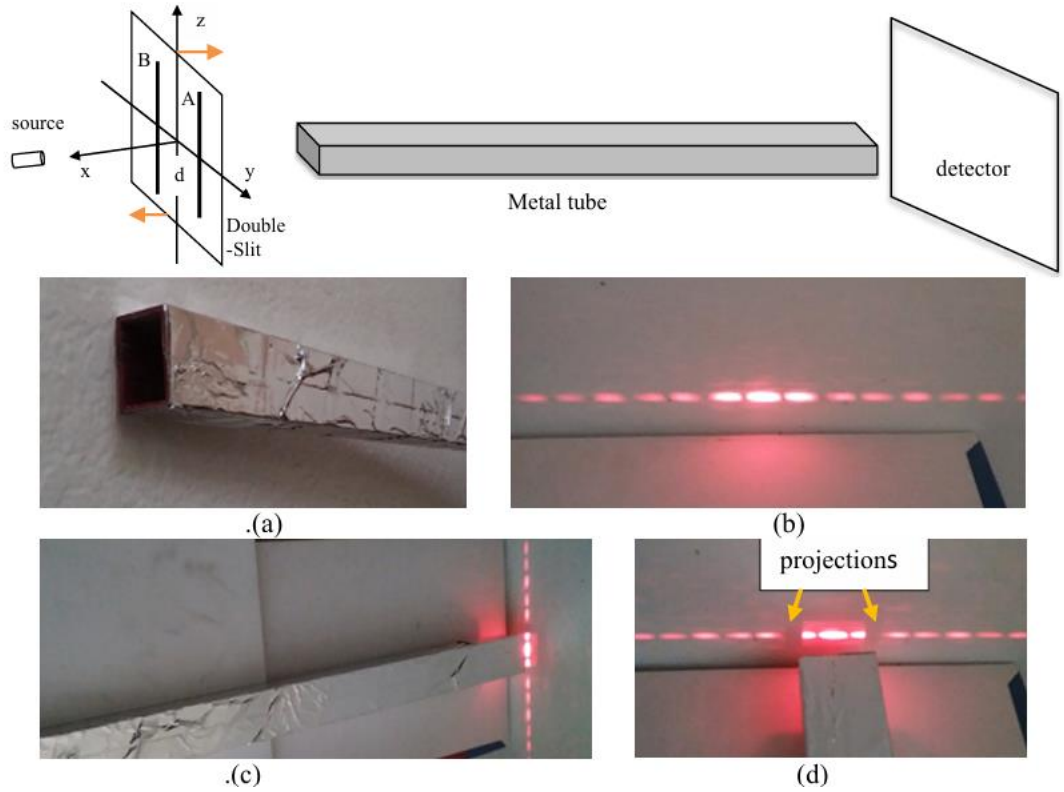


Figure 12: Aluminum-tube-shield and interference pattern

IRREGULAR-DOUBLE-SLIT EXPERIMENTS: LIGHT IS PHOTONS

To study the nature of the light further, in Section 4, we propose and perform the Irregular-Double-Slit Experiments.

Non-Parallel-Double Slit Experiments: PhotoWave Phenomena

Hybrid Pattern: Interference Pattern embedded in Diffraction Pattern:

In the standard double slit experiments, the two slits are parallel. Now we study a non-parallel double slit.

Experiment-11 (Figure 13 and Figure 14)

- As an example, we study the non-parallel-double slit with the angle 17.5^0 between two slits as show in Figure 14.
- **Experimental setup** (Figure 13)**:**
- **Observation:** Figure 14 shows the Hybrid pattern: two interference patterns embedded in two diffraction patterns respectively. Two slits produce two diffraction patterns respectively as they were independent single slit. While two slits produce two partial interference patterns as they were two double slit.

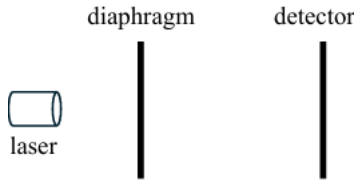


Figure 13. Experimental setup

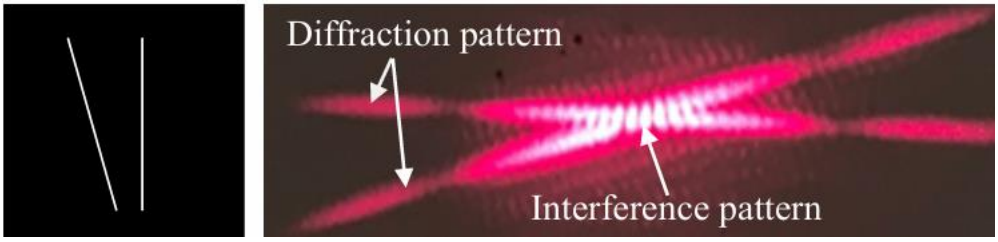


Figure 14: Hybrid Pattern

Angle-Dependence of Hybrid Pattern:
To study the angle-dependence of the Hybrid patterns, we utilize the diaphragm containing 16 two-slits with different angles: 0^0 - 45^0 (Figure 15).

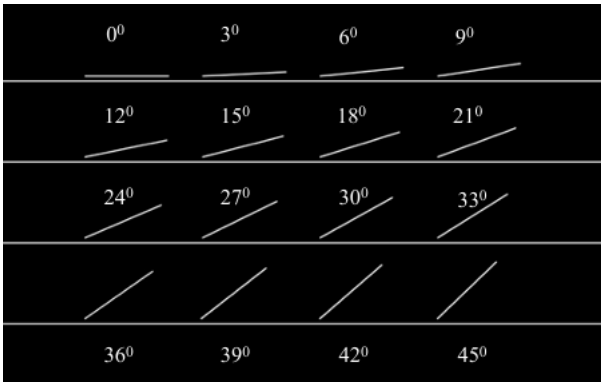


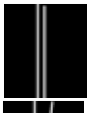
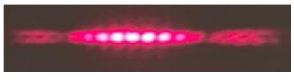
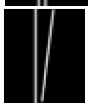
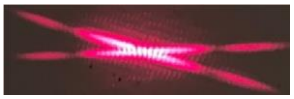
Figure 15: Diaphragm of non-parallel-double-slits with angles: 3^0 - 45^0

The distance between the bottom-ends of the tilt slit and the horizontal slits is 0.3 mm for all of non-parallel-double slit.

Experiment-12: Angle-dependence of Hybride patterns

- **Experimental setup**: Figure 13.
- **Observation**: Table 1 summarizes the angle-dependence of the Hybrid patterns

Table 1: Angle-dependence of Hybrid patterns

angle	2 slits	Patterns	angle	2 slits	Patterns
0^0			3^0		
6^0			12^0		

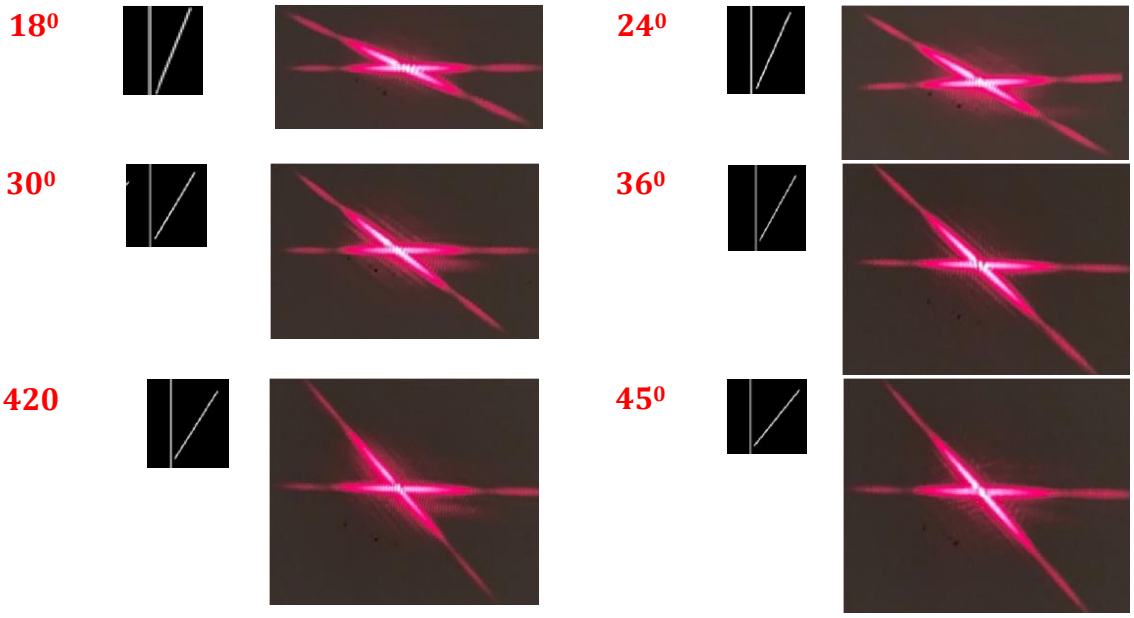


Table 1 shows that the nature and the characteristics of the patterns depend on the angle between two slits. Namely, when the angle between two slits varies from 0^0 to 45^0, the pattern varies from the interference pattern (at 0^0) to the Hybrid patterns to the diffraction patterns (at 45^0 and larger). To interpret consistently the Hybrid patterns is a challenge.

Pattern-Evolution: Lens:

We have shown that the patterns evolve with distance. To study the evolution of the patterns of the non-parallel-double-slit experiment, we use the same experimental setup (Figure 16): The lens is placed at different positions "L" from the diaphragm and thus, the patterns arriving at the input surface of the lens are different.

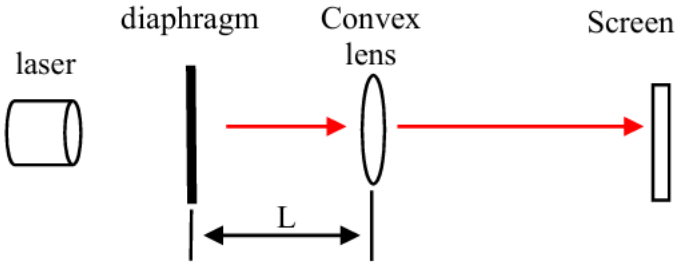


Figure 16: Experimental setup

- **Note:** For all of experiments studying the pattern evolutions with lens, we utilize the same experimental setup of Figure 16.

Experiment-13: Figure 17.

- **Experimental setup**: Figure 16. When placing the lens at different positions L, we observe the pattern evolution (Figure 17). The lens is placed at 10 mm to 1400 mm, $L = 10 - 1400$ mm, from the diaphragm of a non-parallel-double slit. The screen is at 1700 mm from the diaphragm.

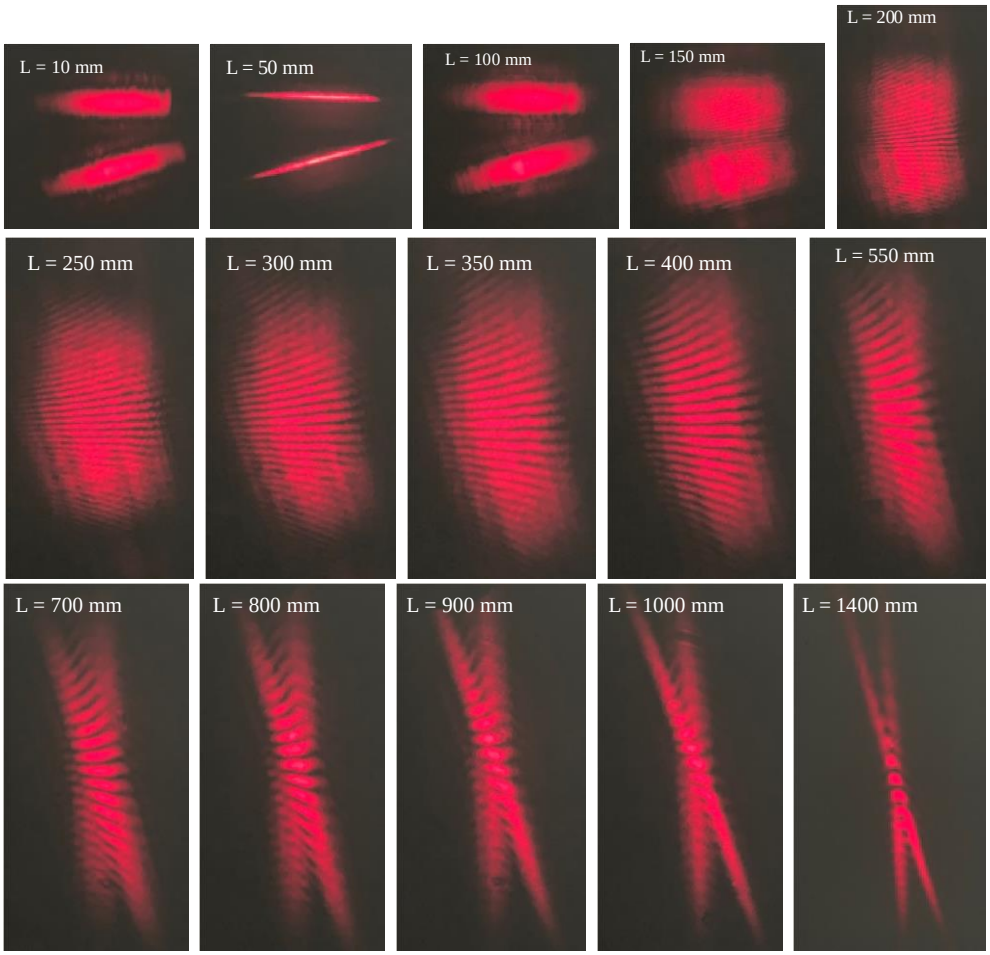


Figure 17: Pattern evolution

- **Observation**: Figure 17 shows the pattern evolution. The patterns are the Particle patterns, when $L = 10 - 150$ mm. For $L = 200 - 700$ mm, we call the patterns the Transition patterns. When $L \geq 800$ mm, the patterns are the Interference + Diffraction Hybrid Patterns.
- **Conclusion:** The non-parallel-double slit experiments show for the first time the phenomenon that the interference pattern is embedding in the diffraction patterns, referred to as the Hybrid patterns. The particle patterns evplve to the Hybrid patterns. The light is photons.

To interpret physically and describe mathematically the phenomenon is a challenge.

Curve-Double Slit Experiments: PhotoWave Phenomena
Arc-Shape Interference Pattern and Point-Symmetry Interference Pattern:
Experiment-14: Figure 18 and Figure 19. The experiment is performed in two experimental setups.

- **Experimental setup-1** (Figure 18): A lens placed between the diaphragm and the detector.

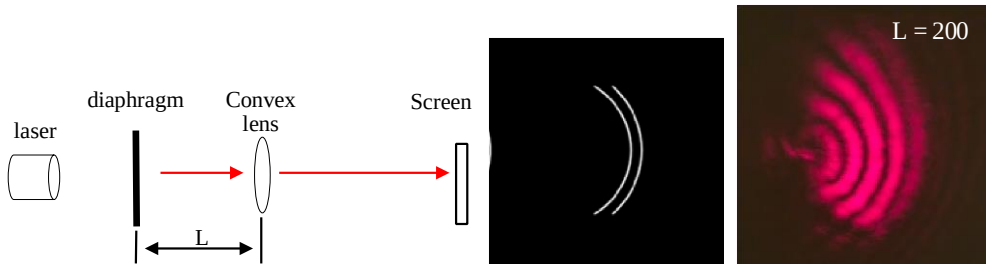


Figure 18: Curve-double slit and its Arc-shape pattern

- **Observation**: Figure 18 shows the Arc-shape Interference Pattern on the detector.

- **Experimental setup-2** (Figure 19): No lens.
- **Observation**: Without using a lens, Figure 19 shows the Point-Symmetry Interference Pattern on the detector.

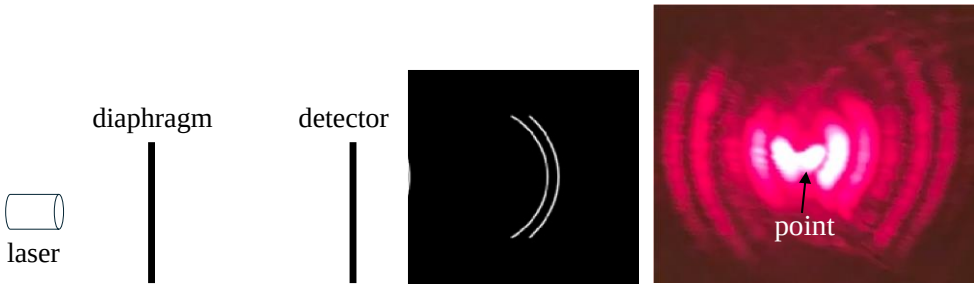


Figure 19: Curve-double slit and its Point-symmetry patterns

Curvature-Dependence of Point-Symmetry Interference Pattern:
To study the curvature-dependence, we show the patterns of the curve-double slit with different curvatures (Figure 20).

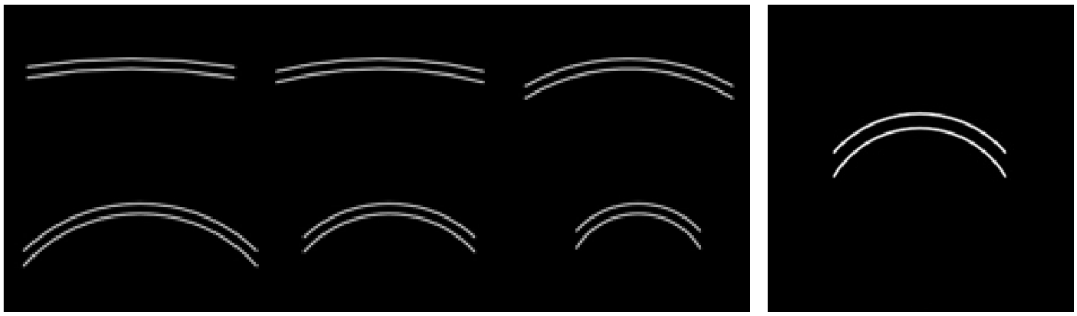


Figure 20: Curve-double slit with different curvatures

- **Note**: We introduce (the right of Figure 20): (1) two radiuses connecting the center of the curve-double slit and the two ends of the curve respectively. (2) the angle between two radiuses. For a parallel-double slit, the angle is 0^0. For a half-circle-curve-double slit, the angle is 180^0.

Experiment-15 (Figure 21).

- **Experimental setup**: Figure 19.

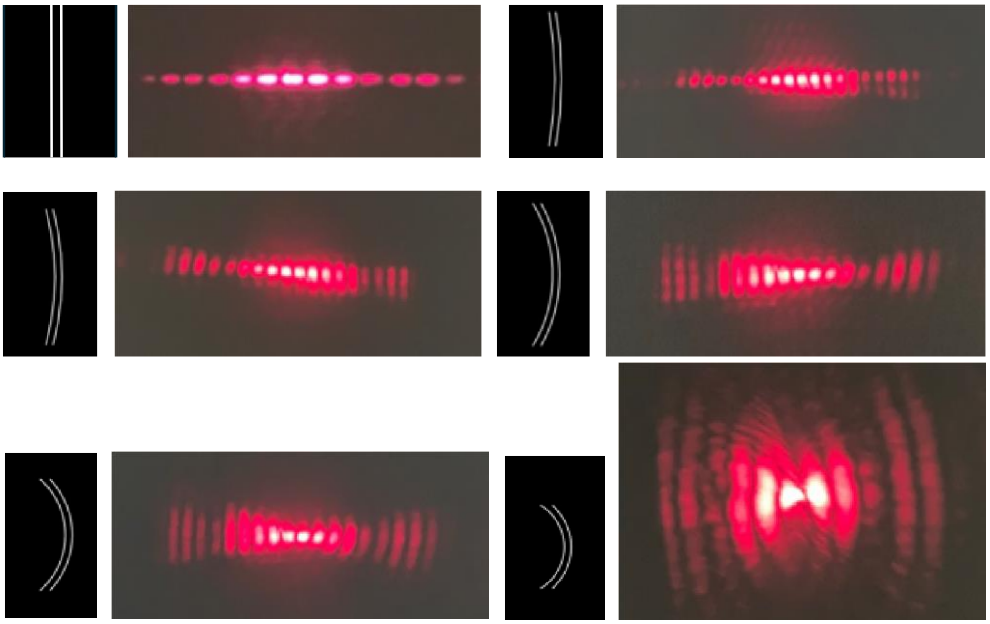


Figure 21: curvature-dependence of Point-symmetry interference patterns

- **Observation**: When the curvature of the curve-double slit increases, the angle increases, the fringes become more curved and extended along the direction of the curve-double slit.

Pattern-Evolution with Lens:

To study the evolution of the patterns of the curve-double slit, we use the same experimental setup (Figure 18): The lens is placed at different positions "L" from the diaphragm and thus, the patterns arriving at the input surface of the lens are different.

Experiment-16 (Figure 22).

- **Experimental setup**: Figure 19.

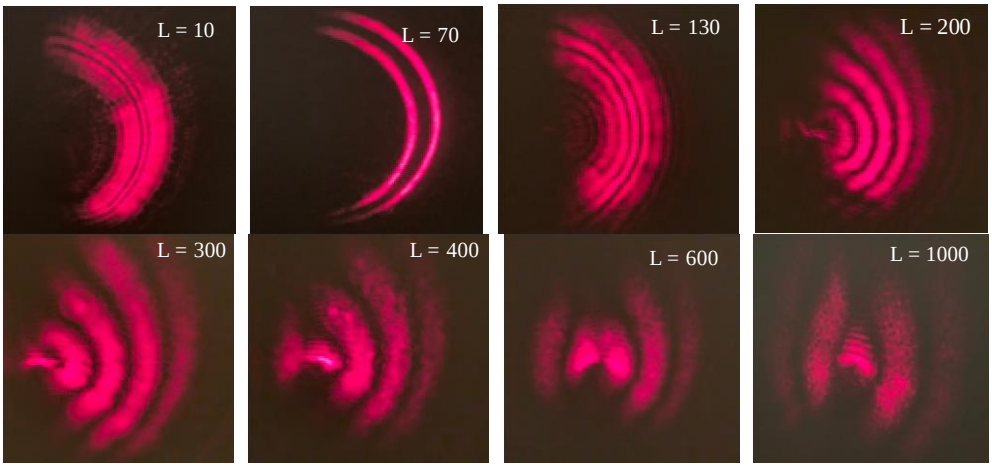


Figure 22: Pattern evolution of curve-double slit

- **Observation** (Figure 22): At $L = 10$ mm, the pattern is Pre-Particle pattern, then evolve sequentially to Particle pattern ($L = 70$), to Transition pattern-1 ($L = 130$), to Arc-shape interference pattern ($L = 200 - 300$), to Transition pattern-2 ($L = 400 - 600$), and finally, to Point-symmetry interference patterns ($L \geq 1000$ mm).
- **Conclution:** the curved-double slit show that the light is phontons and it is photons form the non-interference pattern, the arch-shape interference patterns, and the point-symmetry interference patterns.

Non-Parallel-Curve-Double Slit Experiments: PhotoWave Phenomena
Butterfly-Shape Interference Pattern:
Figure 23 shows Non-Parallel-Curve-Double Slit with different angles.

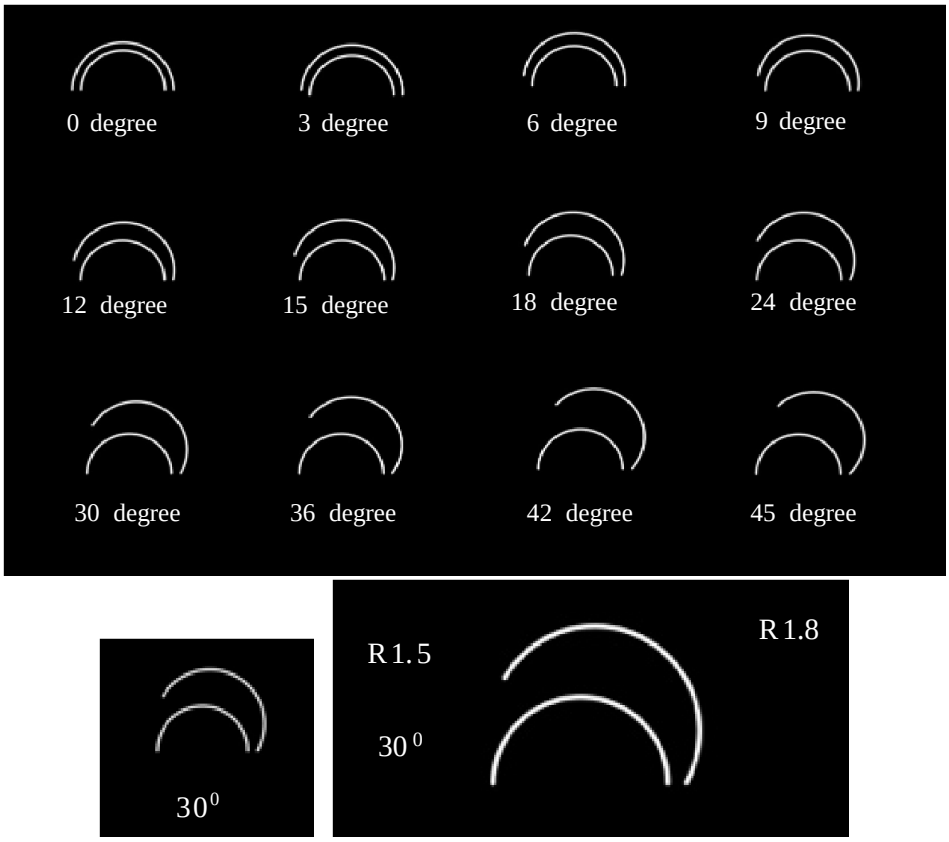


Figure 23: Non-parallel-curve-double slit

Experiment-17: Non-Parallel-Curve-Double Slit Experiments. We show the patterns of the non-parallel-curve-double slit with angle of 30^0 for two setups.

- **Experimental setup-1:** Figure 24. Placing a lens at $L = 600$ mm.
- **Observation** (Figure 24): We observed the interference pattern on the detector, referred to it as the Rest-Butterfly-shape interference pattern.

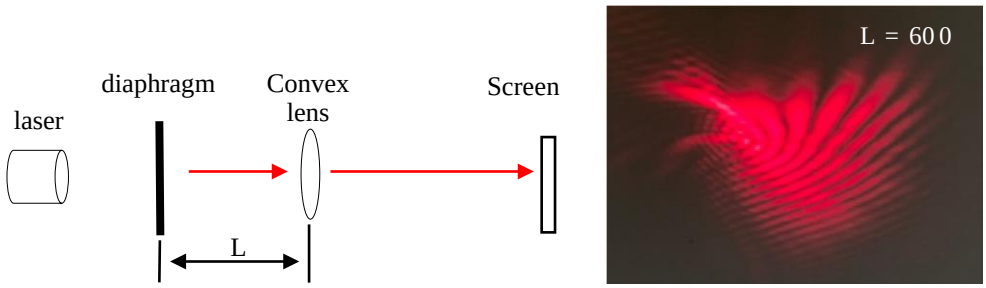


Figure 24: Rest-Butterfly-shape interference pattern

- **Experimental setup-2:** Figure 25. No lens.
- **Observation**: Without using a lens, Figure 25 shows the Interference Pattern on the detector, referred to it as the Flying-Butterfly-shape interference pattern.

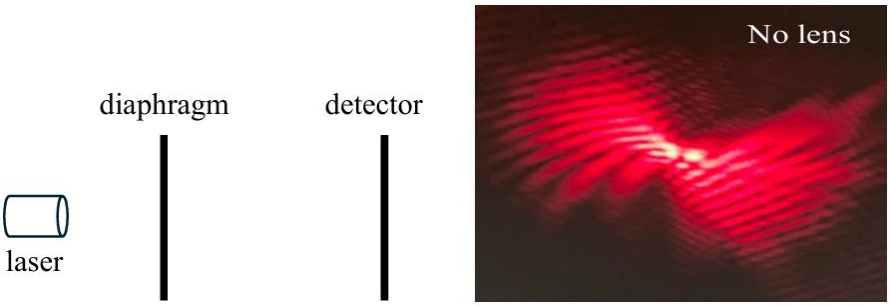


Figure 25: Flying-Butterfly-shape interference pattern

Angle-Dependence of Butterfly-Shape Interference Pattern:
To study the angle-dependence, we show the patterns of the non-parallel-curve-double slit with different angles (Figure 26).

Experiment-18: angle-dependent of Butterfly-shape-interference pattern

- **Experimental setup**: Figure 25.
- **Observation**: Figure 26 shows the angle-dependence of the patterns.

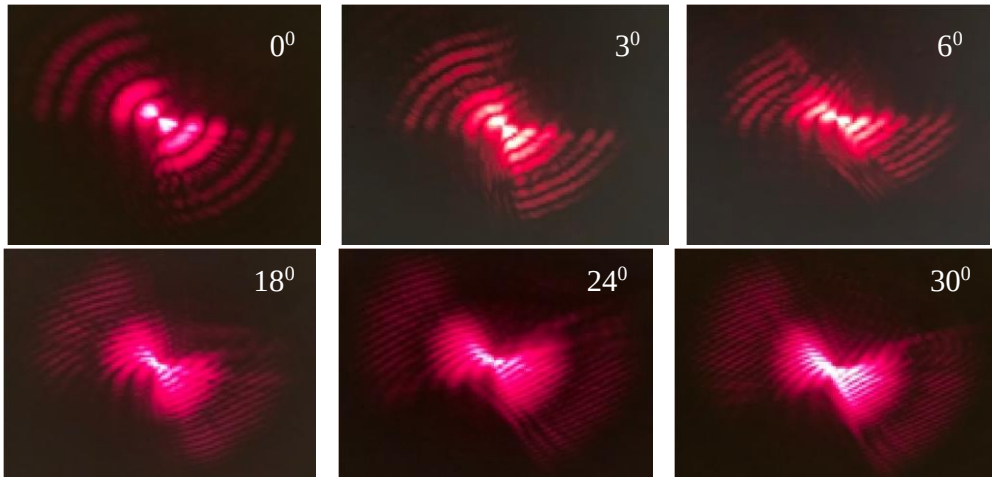


Figure 26: Angle-dependence of Butterfly-shape-interference pattern

Pattern-Evolution with Lens:

Experiment-19: Figure 27 and Figure 28.

- **Experimental setup**: Figure 27, where L in mm

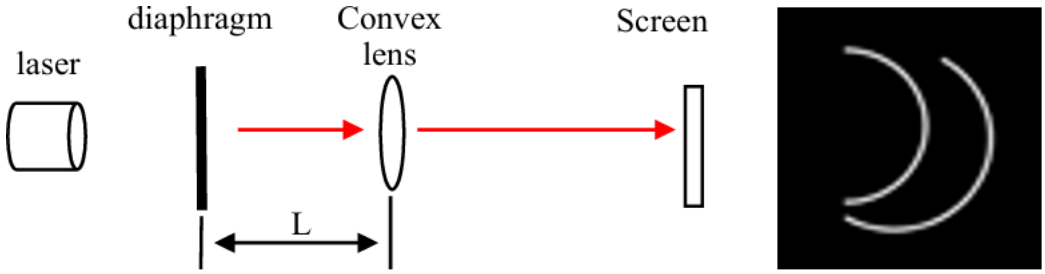


Figure 27: Experimental setup

Figure 28 shows the Pattern evolution of the non-parallel-curve-double slit of angle 30^0.

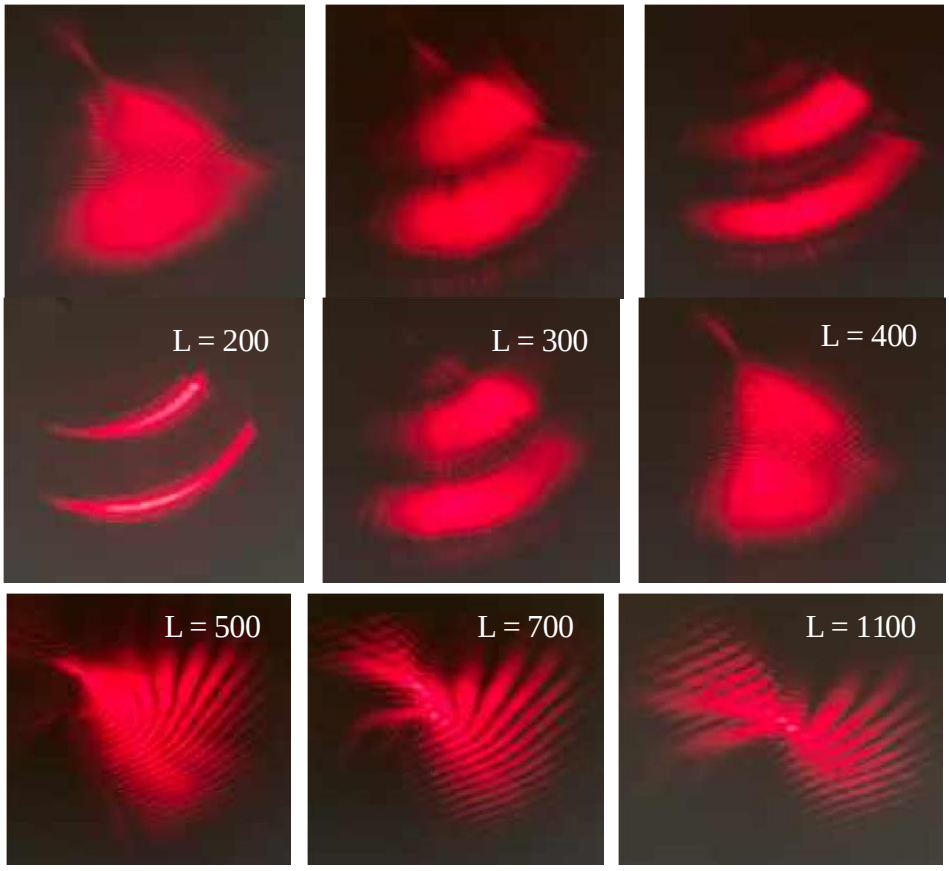


Figure 28: Pattern evolution

- **Observation** (Figure 28): at L =10 - 100 mm, showing Pre-Particle pattern. At L = 200 mm, showing Particle pattern, the image of the non-parallel-curved double slit. At L = 300 - 400 mm, showing Transition pattern-1. At L = 500 mm, showing Resting-Butterfly-shape interference pattern. At L = 700 mm, showing Transition pattern-2. At $L \geq 1100$ mm, showing the Flying-Butterfly-shape interference patterns.

- **Conclution:** Non-Parallel-Curve-Double Slit experiments show that the light is photons.
- **Note**: the patterns gradually evolve, there is no clear cut between different patterns.

SINGLE-SLIT EXPERIMENTS: PHOTOWAVE PHENOMENA

Experiment-20: Pattern evolution of single slit experiment

- **Experimental setup**: Figure 29

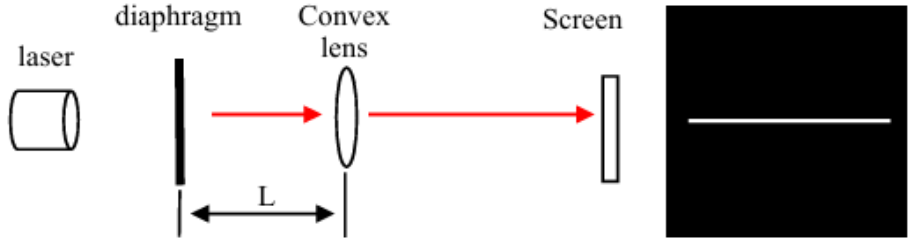


Figure 29: Experimental setup

- **Observation:** Figure 30 shows the pattern evolution.

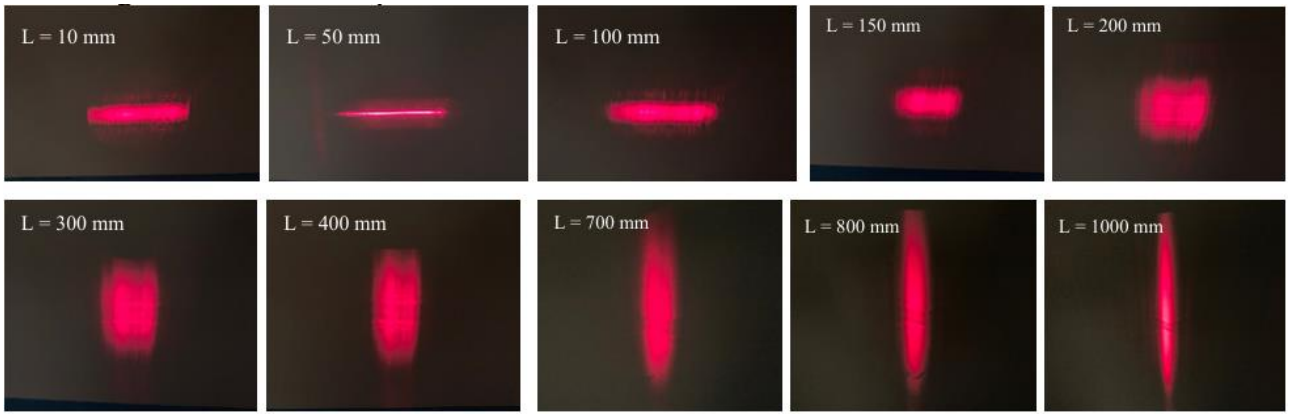


Figure 30: Evolution of pattern of single slit experiment

Figure 30 shows the Particle patterns at L = 10 - 100 mm; the Transition patterns at L = 150 – 700 mm; and the orthogonal diffraction pattens at $L \geq 1000$ mm.

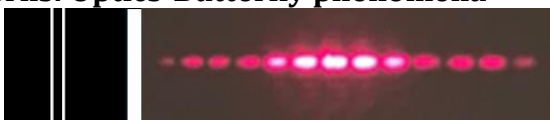
- **Conclution**: The particle patterns show that the light is photons and it is photons that form the non-diffraction and diffraction patterns in the same single slit experiment.

OPTICS-BUTTERFLY-EFFECTS

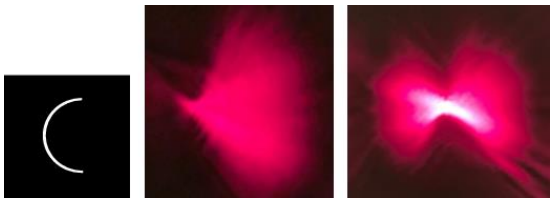
The non-parallel-double slit procuces the Hybrid pattern. The curve-single slit produces the Hourglass pattern. The curve-double slit produces the point-symmetry-interference pattern. The non-parallel-curve-double slit produces the Butterfly-shape interference patter. The single-slit-ring/double-slit-ring produce the ring-interference patterns respectively. The above experiments show that the differences in the structures of slits lead to profound differences in the final patterns (Table 2). We refer to the phenomenon as the ***Optics-Butterfly phenomena***.

Table 2: Different slits vs their patterns: Optics-Butterfly phenomena

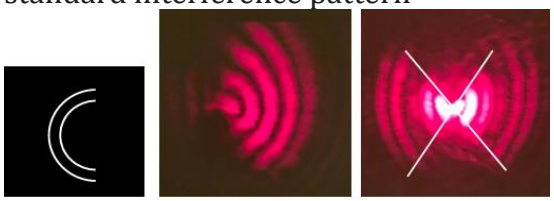
Single slit:
Standad diffraction pattern



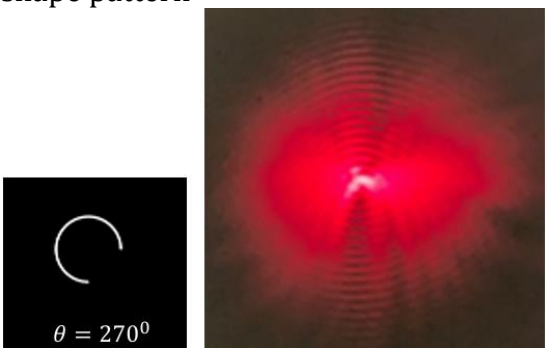
Parallel-double slit:
standard interference pattern



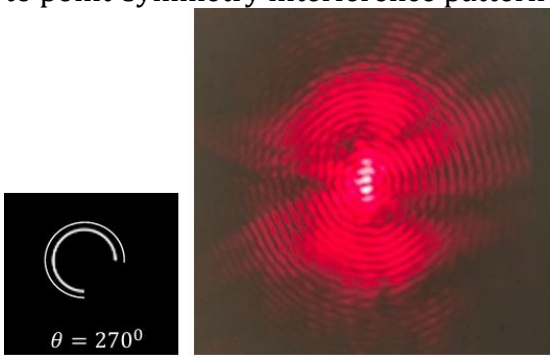
Curve-single slit (1):
fan-shape pattern evolving to hourglass-shape pattern



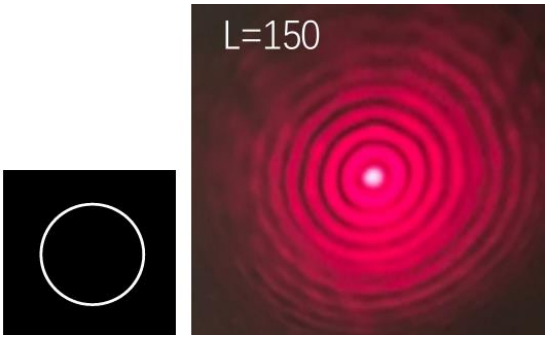
Curve-double slit (1):
Arc-shape interference pattern evolving to point-symmetry interference pattern



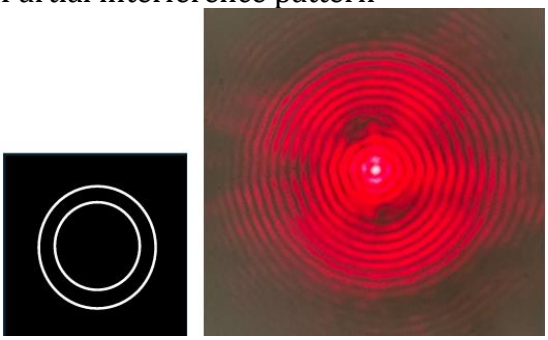
Curve-single slit (2):
Partial interference pattern



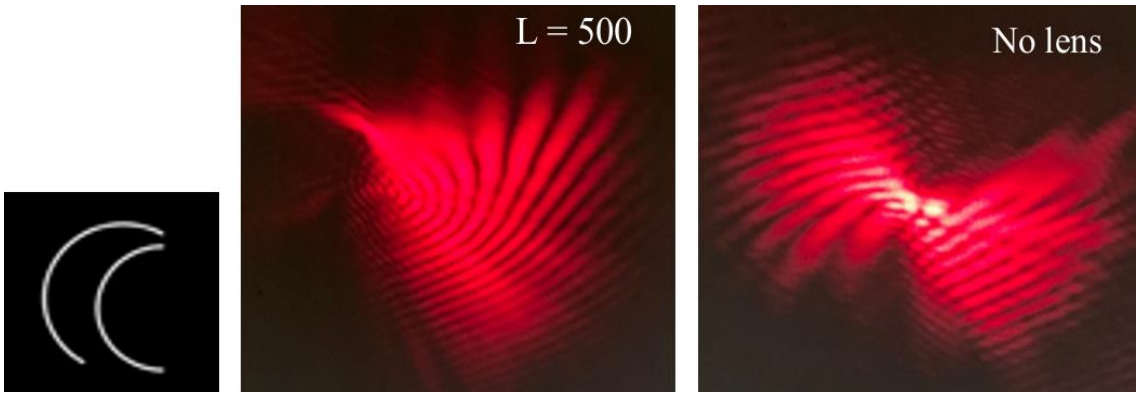
Curve-double slit (2):
Partial interference pattern



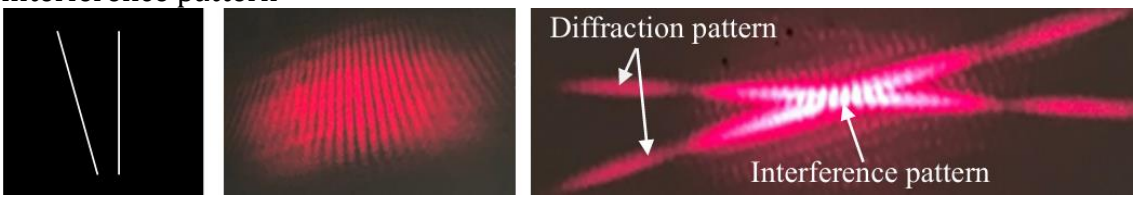
Single-slit-ring:
ring-shape interference pattern



Double-slit-ring:
ring-shape interference pattern

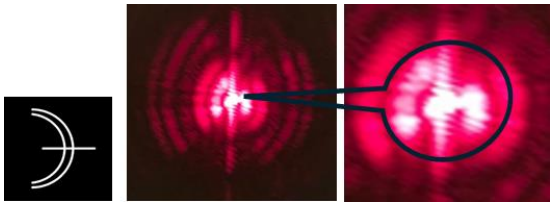


Non-parallel-curve-double slit:
Resting-Butterfly-shape interference patterns evolving to flying-Butterfly-shape interference pattern



Non-parallel-double slit:
Interference pattern evolving to Hybride pattern

Single-slit + curve-single-slit:
Single slit corresponds interference pattern



Single-slit-crossing-curve-double slit:
Single slit corresponds interference pattern

DIRAC-TYPE EQUATION DESCRIBING PHOTONS IN DOUBLE SLIT EXPERIMENT

Dirac-type Equation

To describe the pattern evolution in a double slit experiment is a challenge as mentioned in this article. Namely one needs to describe the Particle pattern, Transition pattern, and Interference pattern in the same experiment consistently and completely.

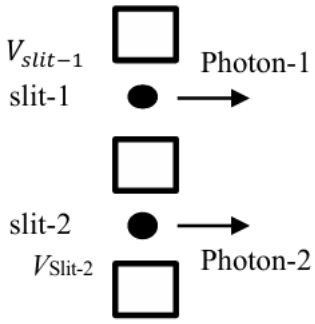


Figure 31: Photons in Double slit

Now let us propose a Dirac-type equation to describe mathematically above patterns. (*) When photon-1 and photon-2 are moving inside the slit-1 and slit-2 respectively (Figure 31), the energies of the photon-1 and photon-2 can be expressed respectively as

$$E_1 = cp_1 + V_{slit-1}, \quad (1)$$

$$E_2 = cp_2 + V_{slit-2}, \quad (2)$$

where, E_1 and E_2 are the energy of the photon-1 and photon-2 respectively, c is the speed of light, p_1 and p_2 are the momentum of the photon-1 and photon-2 respectively, V_{slit-1} and V_{slit-2} are the interaction potential energies between photons and the walls of the Slit-1 and Slit-2 when the photon-1 and photon-2 are in the slit-1 and slit-2 respectively. Eq. (1) and Eq. (2) describe the photon-1 and photon-2 inside the slit-1 and slit-2, respectively.

(*) In Zone-1 (Figure 32), the patterns are Particle patterns which contains two Photon Tracks (Figure 11 and Figure 5b).

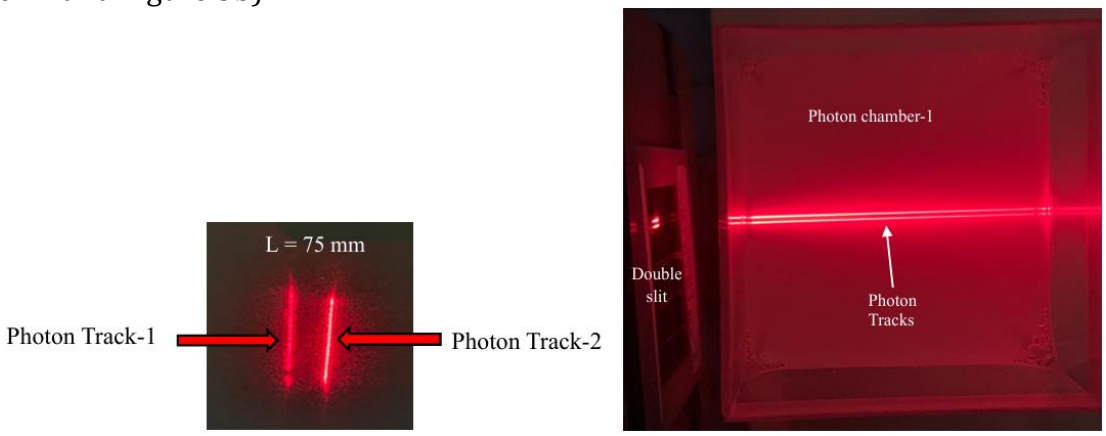


Figure 32: Particle pattern of double slit experiment

The energies of the photon-1 in Photon track-1 and photon-2 in Photon track-2 are respectively,

$$E_1 = cp_1 + V_{1-int-1}, \quad (3)$$

$$E_2 = cp_2 + V_{1-int-2}, \quad (4)$$

where $V_{1-int-1}$ is the potential energy of photon-1 due to the interaction between photons of Photon track-1 in Zone-1; $V_{1-int-2}$ is the potential energy of photon-2 due to the interaction between photons of Photon track-2 in Zone-1 (Figure 32). Eq. (3) and Eq. (4) are the equation describing the photons in Zone-1. (*) In Zone-2 (Figure 33), the patterns are Transition patterns (Figure 11 and Figure 5c).

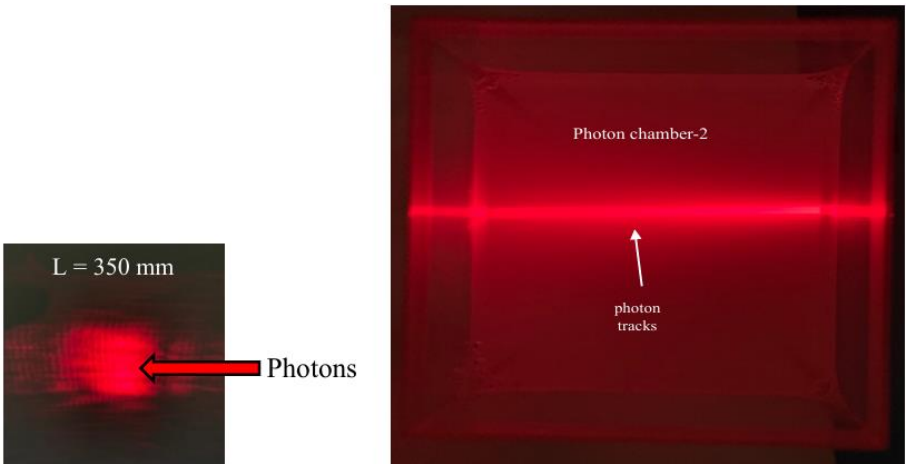


Figure 33: Transition pattern

The energy E of the photon in Transition pattern is,

$$E = cp + V_{2-int}, \qquad (5)$$

where V_{2-int} is the potential energy of the photons due to the interaction between the photons of the Transition pattern in Zone-2. Eq. (5) is the equation describing the photons in Zone-2.
(*) In Zone-3, the energy of the photon is,

$$E = cp + V_{3-int}, \qquad (6)$$

where V_{3-int} is the interaction potential energy of the photons due to the interaction between photons in the same fringe of the interference pattern (Figure 5d and Figure 11).

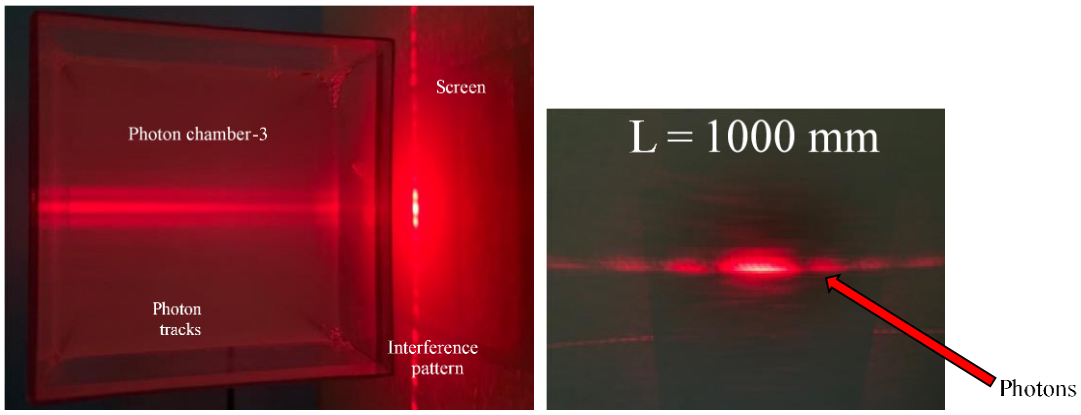


Figure 34: Interference pattern

Eq. (6) describes the photons in Zone-3.

However, in Zone-3, the photons distribute as waves and produce the interference pattern. To describe the interference pattern, we use the same Eq. (6) and utilize the probability wave function ψ and operators,

$$E \sim i\hbar \frac{\partial}{\partial t},$$
$$p \sim -i\hbar \frac{\partial}{\partial r}$$

Substituting the ψ and operators into Eq. (6), Eq. (6) becomes the Dirac-type equation of photon,

$$i\hbar c \frac{\partial \psi}{c\partial t} + i\hbar c \frac{\partial \psi}{\partial r} = V_{3-int}\psi \qquad (7)$$

The Eq. (7), like Dirac equation, has the form in which the space and time derivatives are on an equal footing. The wave solution of Eq. (7) is

$$\psi = \psi_0 \exp \mathrm{i}(k \cdot r - \omega t) \qquad (8)$$

EXPERIMENTS FOR TESTING INTERACTION BETWEEN PHOTONS

To test the interaction potential energy due to the interaction between photons, we utilize exactly the same experimental setup. Then do the experiments in two steps:

1. First step: using the laser light beam, multi photons;
2. Second step: using single photon one at time.

If Particle pattern, Transition pattern and interference pattern are exactly the same for two steps respectively, then there is NO interaction between photons.

If Particle pattern, Transition pattern and interference pattern are different in two steps respectively, then there is interaction between photons.

SUMMARY AND CONCLUSION

We proposed the equations, Equation (1) to Equation (6), to describe photons of different patterns at different positions (inside each slit of the double slit, in Zone-1 to Zone-3), respectively, in a double slit experiment. Those equations are based on the same energy-momentum relation and thus, have the same forms. To describe the interference patterns, utilizing the wave function and the operators, we convert Equation (6) to the Dirac-type Equation (7).

DISCUSSION AND CONCLUSIONS

The phenomena of all comprehensive double slit experiments and irregular-double slit experiments in this article are consistent. The phenomena of the non-interference patterns evolving to the interference patterns are universal and mystery. The comprehensive double slit experiments and irregular-double slit experiments show that the light is photons, and it is the photons that form the wave-distribution, reffered to it as the PhotoWave phenomena. The experiments of this article show how the geometry of the slits affects the final interference patterns. The comprehensive double-slit experiments show the photon nature of light. It reveals the wave-particle duality of photons, namely, the photons are particle, but distribut as wave. The experiments need to be studied further, might need new setups and interpretations.

The non-parallel double-slit experiments show the Hybride pattern and challenge the standard double-slit theories and indicate the need of new explaination.

The curved double-slit experiments show the arc-shape interference pattern and the point-symmetry interference pattern. The non-parallel-curve double-slit experiments show the Butterfly-shape interference patterns.

The above new experiments/phenomena show the sensitive dependence of interference patterns on the structure of the double slit, we referred to it as the "Optical-Butterfly-Effect".

To interpret consistently the PhotoWave phenomena of the comprehensive double slit experiments and irregular-double slit experiments is a challenge to existing theories of light, and demindes a complete explanation. For this purpose, we propose a Dirac-type equation to describe the Particle pattern, Transition pattern and interference pattern produced by photons

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