Curved Interference Pattern Created by Photons Behaving as Particle—Double Slit Experiment Still Has Much to Offer

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Research Article

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Curved Interference Pattern Created by Photons Behaving as Particle
---Double Slit Experiment Still Has Much to Offer

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Abstract
Young’s double slit experiments, which represent the mystery of quantum mechanics, have been described by either the classical wave, or quantum probability waves or pilot waves. Recently, the novel experiments show that the interference patterns of the double slit/cross-double slit experiments may be curved. The previous phenomena of the light bending contain the gravity bending and Airy beam curving transversely. The curved Airy beam is interpreted by the quantum Schrödinger’s wave equation and electromagnetic wave theory. To study the curved interference patterns of the comprehensive double slit experiments, we study the underlying physics first, namely, to study whether the light beam/photons behave as wave or as particle before forming the curved interference pattern. In this article, the comprehensive double slit experiments are performed, which show: (1) the fringes of the curved interference pattern are created independently and may be create partially; (2) the longitudinal shield and the metal tube inserted between the slide and the detector has no effect on the interference pattern. The experimental observations suggest that, before forming the curved interference pattern on the detector, photons behave as particles, which can be referred as “wave-particle-coexistence”. The phenomena provide the comprehensive information/data for the theoretical study.

Keywords: double slit experiment, cross-double slit experiment, mystery of double-slit experiment, light bending, curved interference pattern, wave particle duality, complementarity principle

Declaration: this article has no interesting conflict.

1. Introduction

The evolution of the concept of the nature of light/photons has a long history. In 1801, Young performed a double slit experiment[1][2], which, for the first time, demonstrated that light could
behave as waves, namely, the wave theory of light of Huygens (1678) was correct. 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 interfere.

Einstein (1905) proved theoretically that light is quanta, which combining with Young’s double slit experiment led to wave-particle duality. Feynman (1956) called “[the double slit experiment] contains the only mystery [of quantum mechanics]” [3]. Moreover, the nature of photon truly puzzled Einstein. He wrote to M. Besso: “All these 50 years of conscious brooding have brought me no nearer to the answer to the question: What are light quanta?” [4].

We argue that one of the reasons why the mystery of the double slit experiments being long-standing is the lack of the experimental data. The 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, the novel experiments are performed, which show that the interference patterns of the double slit/cross-double slit experiments and the diffraction pattern of the grating experiments are curved continuously [5] [6] [7]. Hereafter, we referred both the “interference pattern” and “diffraction pattern” simply as the “pattern”.

The light bending shown in two phenomena: the light beam is bended by gravity [8] and Airy beam curved transversely. The gravity bending is explained as that it is caused by the curved space-time. The curved Airy beam is interpreted by the quantum Schrödinger’s wave equation [9] and electromagnetic wave theory [10].

In this article, as the first step of studying the curved pattern, we start with experimentally studying the underlying physics. Namely to test whether the curved patterns are formed by photons behaving as particles or by light beams behaving as waves. To interpret the curved patterns consistently is a challenge. We perform the comprehensive double slit experiments to explore the behavior of the photons before forming the curved interference patterns on the detector. One of characteristics of those experiments is that the experimental results are visually observable without ambiguity.

2. A Model and Experiment Apparatus

To precisely describe the double slit, we introduce a model, in which the slide of a double slit and its right-side neighborhood is represented as a “virtual box” (Figure 1).
The model is divided into 3 zones: zone-1 (Z-1) is from the source to the left side of the slide of the double slit, which is the left-side of the virtual box, the virtual box is zone-2 (Z-2), and zone-3 (Z-3) is from the right side of the virtual box to the detector.

In this article, we create the curved pattern first, and then study how photons behave in zone-3 before arriving on the detector.
To test whether photons behave as waves in zone-3, we insert: (1) longitudinal “wave shield(s)” (Figure 2a), denoted as “shield”; (2) transverse “wave blocker(s)” (Figure 2b), denoted as “blocker”; (3) longitudinal metal tube (Figure 2c), denoted as “tube”; all near detectors. The shield’s and tube’s orientations are from the center of the double slit pointing to the center of the pattern respectively. The distance between the double slit and the detector is 110 inches (2750 mm). Note that the drawings in Figure 2 are not to scale.

We want to observe whether the curved pattern would be disturbed in the situations shown in Figure 2. In the rest of the article, we show that photons behave as particles in zone-3 before forming the curved pattern.

3. Experiment with Shield

**Experiment-1** (Figure 3): Study the effect of the shield on the curved pattern.

To form a curved pattern (Figure 3a), the slide is rotated, say 75 degrees, around Y-axis. To show the curved pattern, we draw the yellow line in Figure 3a.

**Experimental setup** (Figure 2a): Inserting a longitudinal “shield” (dark gray) made of Aluminum into the experimental apparatus between the double slit and detector. The shield’s orientation is from the center of the double slit points to the center of the first-order-fringe. Shield is 10 inches (25 cm) long, 5/8 inch (1.5 cm) wide, and 1 mm thick. The distance between the double slit and the detector is 110 inches (275 cm).

According to the wave theory, the shield separates waves and thus prevent waves from interfering. An analogy is a breakwater that break water waves.
Observation (Figure 3b and 3c): (1) the comparison of Figure 3a and 3b indicates that the shield does not affect the interference pattern at all; (2) there is the projection of the shield at the middle of the first-order fringe (Figure 3c).

Conclusion: the observed phenomena would be expected if photons behave as particles.

Discussion: on the one hand, the photons behave as particle, on the other hand, the photons form the interference pattern. This is a wave-particle paradox.

4. Experiment with Metal Tube

Experiment-2 (Figure 4):

Experimental setup (Figure 2c): Inserting the tube between the double slit and detector (Figure 4d), and 1 inch (2.5 cm) from the detector.
Figure 4 Curved Pattern with and without metal tube

The metal tube’s orientation is from the center of the double slit points to the center of the pattern. The dimension of the tube is 16 mm x 24 mm x 1220 mm, and 2 mm thick. The distance between the double slit and the detector is 110 inches (275 cm).

According to the wave theory, the metal tube should prevent waves from interfering.

**Observation** (Figure 4b and 4c): photons passing through the tube form four center fringes on the detector. The two red spots on the two vertical walls at the “entrance” of the tube indicate that the vertical wall block some photons and form projection on the detector. Here the “entrance” stands for the opening of the tube that photons enter the tube. The two projections are next to the four center fringes. The remaining photons form the rest pattern that is the same as there was no tube.

**Conclusion**: the metal tube does not affect the pattern at all. The observed phenomena would be expected if photons behave as particles, but not as waves.

**Discussion**: on the one hand, the photons behave as particles passing through the long tube, on the other hand, the photons form the interference pattern. This experiment shows a wave-particle paradox.

5. Experiment with Blocker

**Experiment-3** (Figure 5):

**Experimental setup** (Figure 2b): place a blocker one inch away from the detector.
Observation (Figure 5b): the blocker blocks the half of the zeroth-order fringe, the whole \( m = 1 \) fringe and half of the \( m = 2 \) fringe. The remaining fringes are not affected.

Conclusion: the fringes are formed independently and partially. Only particles, not waves, may behave this way. On the other hand, the photons form the interference pattern.

Discussion: the experiment-3, as experiment-1 and -2, shows a wave-particle paradox.

6. Discussion: On Light Bending

Experiment-1, experiment-2 and experiment-3 show that the light beam behaves as particles (photons) before arriving at the detector and forming the curved pattern.

We re-study the straight and curved patterns of the double slit experiments (Figure 6 to Figure 8).

Indeed, in the normal double slit experiment, after passing the slide, photons propagate as particles and land on the position of each fringe respectively \([11][12]\), namely, photons as particles bend along Y-direction to land on a straight line to form different fringes (orange-colored light rays and fringes) (Figure 6).
In this sense, the straight pattern of the normal double slit experiment represents the “light bending”, referred as “straight-line light bending”. Namely the normal “interference pattern” is the “straight-line light bending”.

After the slide rotated around Y axis, photons pass through the slide, behave as particles and land on the detector along the curved line to form fringes (green-colored light ray and fringes Figure 7).

The curved pattern represents the “light bending” as well, referred as “curved-line light bending”, or “curved pattern”. In the phenomena of the “curved-line light bending”, the photons bend not only along the Y direction, but also in Z-direction. The net bending is the combination of both bending (Figure 7).

We suggest an interpretation to explain the phenomenon of the curved pattern. A laser source emits photons as a beam of particles (as proved experimentally [11] [12]). Those photons travel into the virtual box.

In the language of “wave theory”, the function of the “virtual box” is a process of “forming” the distribution of the light beam as waves.

In the language of “particle theory”, the function of the “Virtual box” is a process of “grouping” photons into different groupsstreams (denoted the process as “grouping”). Different groups 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 groupsstreams 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 in this article), 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.

In the static double slit experiments, photons are “forming” or “grouping” to propagate to the straight-line positions of the fringes, i.e., photons bended along a straight line. In the dynamic double slit experiments, photons are “forming” or “grouping” to propagate to the curved-line positions of the fringes, or to the expanded positions of the fringes, or to the inclined positions of the fringes.

Note that in which-way 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 wave distribution still exists. As we did in the above comprehensive-double slit experiments, each blocker can be considered as a measurement tool and does not affect the interference distribution at all.

The mechanism of “forming” or “grouping” is mystery.

The Feynman’s mystery of the double slit experiments becomes more mysterious.

### 7. Summery

Based on three facts discovered from above experiments, (1) shields/blockers/metal tube have no effect on fringes of the curved pattern, 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., zone-3, photons behave as particles. The above phenomena are naked-eye-visible.

On the one hand, in the normal double slit experiments, it is interpreted that the light behaves as a wave and creates an interference pattern on a detector. Indeed, the interference patterns do exist in the above experiments.

On the other hand, we have discovered experimentally that, in zone-3, photons indeed behave as
particles, which would not be expected if light behaves as waves.

This seems a “wave-particle coexistence”.

The significances of the novel double slit experiments of this article are:

(1) show that the curved patterns are formed by photons behaving as particles, not as waves; and (2) provide comprehensive phenomena/information for developing theoretical model to explore the mystery of the double slit experiments.

Let us compare the phenomena of the curved light.

| cause  | Gravity bending light | Curved Airy beam | Curved pattern |
|--------|-----------------------|------------------|---------------|
| phenomena | gravity | Interfered waves | Light bended | Light Beams move along curved trajectory | Photons behave as particle and form curved pattern |
| theory | General relativity | Quantum theory, Maxwell theory | Right-hand rule and right-hand rule |
| applications | Gravity lenses | biomedical applications |

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

It is challenge to interpretate the curved patterns of the experiments of the double slit/cross-double slit/grating, when the slide rotating, respectively, around X-axis, Y-axis and Z-axis clockwise and counterclockwise consistently.

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

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