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Observation of Which-Way-2D-Cross-Double-Slit Experiments: Violation of Bohr's Complementarity Principle

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Abstract Young's one-dimension-double-slit experiment represents the basic mystery of quantum world and was extended to which-way-1D-double-slit experiment. To explore the mystery, 2D-cross-double-slit apparatuses have been proposed, which consists of more than one double-slits intersecting to each other. In this article, we report which-way-2D-cross-double-slit experiments by detecting which slit of a double-slit of 2D-cross-double-slit apparatus a photon would pass through. The experimental results show that photons passing through the detected double-slit behave as particle, while photons passing through other undetected double-slit(s) distribute as wave in the same experiment with the same apparatus. Namely the particle nature and wave distribution coexist, which violates Bohr's complementarity principle. We suggest that photon's "particle nature" is intrinsic, while the term "wave nature" represents a wave-like distribution, which is a consequence of movement of photon as particle. It is a challenge to interpret mathematically those observations consistently.

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

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1. Introduction

Young's double-slit experiments as 1D-double-slit experiments was interpreted as that each photon has arrived by both slits at the same time and created interference pattern. However, the light is always found to be absorbed at the screen at discrete points, as individual particles; the interference pattern appears via the varying density of these particle hits on the screen. Young's 1D-double-slit experiment led to wave-particle duality. Feynman called it "*a phenomenon […] has in it the heart of quantum mechanics. In reality, it contains the only mystery [of quantum mechanics]*" [1]. J. Taylor states: "*And yet we have no clue how any of the fundamental facts of quantum mechanics including wave-particle duality, […], or the double-slit experiment - that disarmingly simple setup - actually work*." [2]. Moreover, the nature of photons really puzzled Einstein. He wrote to M. Besso: "*All these 50 years of conscious brooding have brought me no nearer to the answer to the question: What are light quanta?*" [3]. The 1D-double-slit experiment has also been performed with varying numbers of slits, e.g., parallel-multi-slits [4].

To explore the nature of photon further, 1D-double-slit experiment was extended to which-way-1D-double-slit experiment. Technically feasible realizations of which-way experiment were proposed in the 1970s [5,6]. A photon is observed near a slit by utilizing a photoelectric-detector to register the photon, practically it blocks the path of photons, namely equivalent to cover a slit [7,8]. When the photon is detected, the interference pattern disappears. Based on the which-way-1D-double-slit experiment, it is concluded that photons can behave as either particles or waves, but cannot be detected as both at the same experiment. Which-way-1D-double-slit experiment confirms the complementarity principle.

The operational definition of "wave/particle" stands for "ability/inability to create interference". [9,10,11].

Recently, for studying both the mystery of double-slit experiments and nature of photon further, the 2D-cross-double-slit apparatuses have been proposed [12,13], and experiments were performed [14]. The experimental results challenge the standard interpretation of 1D-double-slit experiments.

The which-way-1D-double-slit experiments show the particle nature of photon only. It is nature to ask that, when one performs which-way experiment by utilizing 2D-cross-double-slit apparatus, what patterns would we expect? Namely, since a 2D-cross-double-slit apparatus consists of two or more double-slits, when we observe at one slit of one double-slit photons passing through, would we detect particle nature of photon passing through all double-slits, or would we detect wave distribution of photons passing through other un-observed double-slit(s)?

According to the complementarity principle, we can detect only one nature of photon, either particle or wave, but not both. If we observe both natures, it would be a paradox.

Figure 1 and Figure 2 show the difference between 1D-double-slit experiments and which-way-1D-double-slit experiments respectively [15], where the dashed slit-A represents that photons passing through slit-A is registered on a photoelectric-detector, namely slit-A is covered by photoelectric-detector.

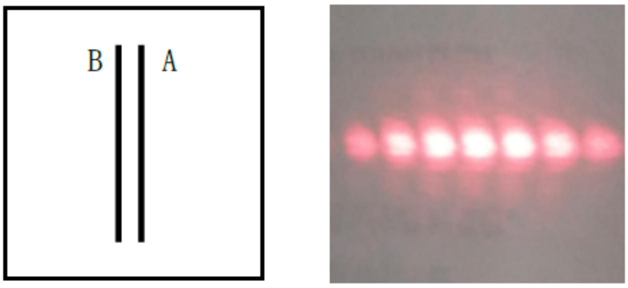

Figure 1. 1D-double-slit

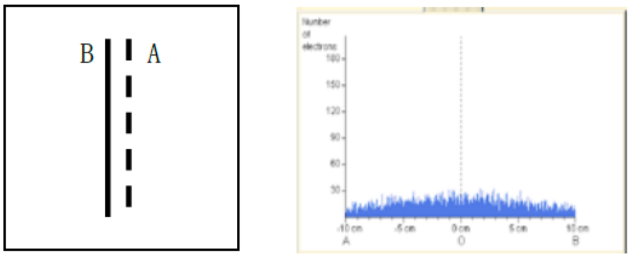

Figure 2. Which-way-double-slit

In this article, we report which-way-2D-cross-double-slit experiments. For clearly show the significant contents of which-way-2D-cross-double-slit experiments, we compare 2D-crosse-double-slit experiments and which-way-2D-cross-double-slit experiments side by side in Section 4.

2. Slides of 2D-Cross-Double-Slit

To clearly show the significant difference, let's compare a commercial slide consisting of four 1D-double-slits (Figure 3) and the slide consisting of six varieties of 2D-cross-double-slit (Figure 4) [14].

Figure 3. Double-slit

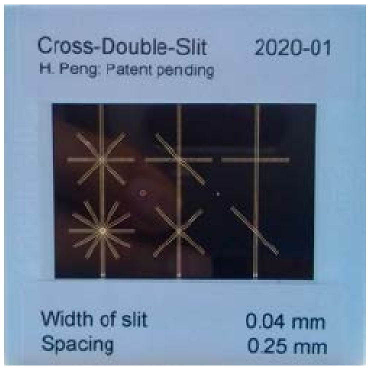

Figure 4. Cross-double-slit

The slide of Figure 4 consists of three vertical double-slits. Horizontal double-slit, tilt-double-slit and multi-tilt-double-slit cross to each vertical double-slit respectively. All slits have the same width of 0.04 mm, and all double-slits have the same space of 0.25 mm.

3. 2D-Cross-Double-Slit Experiments

In this section we briefly present a 2D-multi-tile-cross-double-slit experiment, which is not reported before [14]. The configuration of the experiment: a laser source points to a slide two feet away, and a detection screen is 20 feet away from the slide.

Experiment-1 (Figure 5): A 2D-multi-tilt-cross-double-slit (on the left) and its 2D-multi-tilt-cross-interfernce pattern (on the right). The 2D-multi-tilt-cross-double-slit consists of six double-slits. Each double-slit rotates 30^0 with respect to the double-slit next to it.

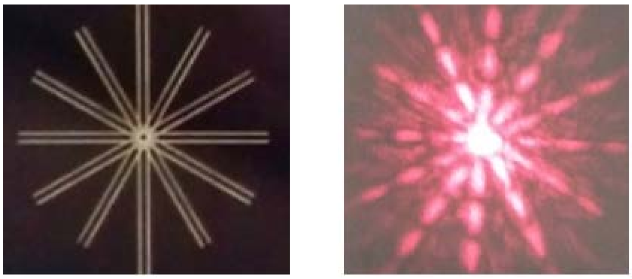

Figure 5. 2D-multi-tilt-cross-double-slit experiment

Shinning laser light at the intersection of the multi-tilt-cross-double-slit, we observe the 2D-interference pattern created on the detection screen. Photons passing through one slit interfere with photons passing through its paired slit to create the interference pattern, but do not interfere with those photons passing through other slits. How can photons make this "decision"? It is a mystery that is more mysterious than double-slit mystery.

The zero-order fringes of six interference patterns are overlapped. If using lines to connect first-order fringes of each of 1D-interference patterns created by different double-slits respectively, then the lines are closed to form an octagon. Therefore, we argue that to increase the number of tilt-double-slits, the shape of the closed line will be closer and closer to a circle. The same for the second-order fringes, and so on.

4. Which-way-2D-cross-double-slit Experiments vs. Complementarity Principle

During the which-way-1D-double-slit experiments, a photoelectric-detector that can register the received photons, is placed behand a slit, which is represented by dashed-slit (Figure 2). When the photoelectric-detector "observes"/detects a photon, the photon is absorbed, namely, the photoelectric-detector blocks the traveling path of photons. The purpose of which-way-2D-cross-double-slit experiments in this paper is to test whether photons can behave as both particle and wave distribution in the same experiment. Thus, we just block one of slits without counting blocked photons.

To show clearly the differences between regular 2D-cross-double-slit experiments and which-way-2D-cross-double-slit experiments, we show apparatuses/observations side by side. Figure 6, Figure 8 and Figure 10 show regular 2D-cross-double-slit experiments respectively, while Figure 7, Figure 9 and Figure 11 show which-way-2D-cross-double-slit experiments correspondingly.

Now let's perform which-way-2D-cross-double-slit experiments.

4.1. Observations

Experiment-2 (Figure 7): Which-way experiments with 2D-cross-double-slit.

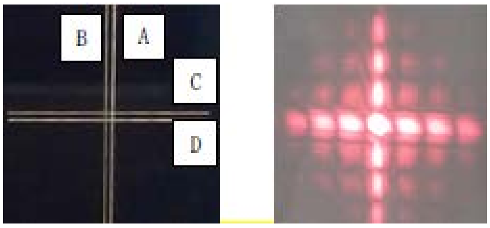

Figure 6. Cross-double-slit Experiment

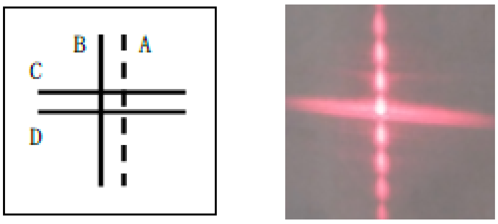

Figure 7. Which-way-cross-double-slit experiment

Slit A and slit B pair up to form double-slit-AB, while slit C and slit D pair up to form double-slit-CD that is perpendicular to the double-slit-AB. The intersection has shape of square. Double-slit-CD (AB) has reflection symmetry with respect to double-slit-AB (CD). Without blocking slit-A, we obtain 2D-interference patterns as show in Figure 6. The 1D-Double-slit-AB creates the horizontal interference pattern, while the 1D-double-slit-CD creates the vertical interference pattern.

In the which-way experiment, the dashed-slit-A in the left drawing of Figure 7 indicates that slit-A is blocked. We have two interpretations: (1) Photons passing through slit-B form pattern showing particle nature; (2) a photon passing slit-C needs to "find" a photon passing through the "paired slit", slit-D, to interfere; (3) the photons passing through two non-paired slits, say slit-B and slit-C, will not create an interference pattern.

The regular interpretation of which-way-1D-double-slit experiments seems impossible to explain how each photon travels through both double-slit-AB and double-slit-CD at the same time and show different natures of photon accordingly.

It is a challenge to interpret how a photon "senses": (1) which slit it passes through; (2) which photons it will interfere with, then to create interference pattern accordingly. Namely, photons passing through slits A and B create the horizontal particle pattern; photons passing through slits C and D create the vertical interference pattern. How can a photon behave like that?

Which-way-2D-cross-double-slit experiment shows the following:

1. The horizontal interference pattern (Figure 6) due to double-slit-AB *disappear*, which is the same as that shown in Figure 2, the latter is interpreted as that the photons passing through double-slit-AB behave as particle.
2. There is still vertical interference pattern due to double-slit-CD, which implies that photons passing through slits C and D behave as wave.
3. Both double-slits create patterns independently.

Adopting the operational definition: "wave/particle" stands for "ability/inability to create interference" [9,10,11], then we say, photons passing through slits A and B behave as particle in this Which-way experiment. Thus, wave distribution and particle nature of photons coexist, which violate complementarity principle.

The same phenomena occur for Which-way-tilt-cross-double-slit and Which-way-multi-tilt-cross-double-slit, as shown in Figure 9 and Figure 11.

Experiment-3 (Figure 9): Which-way-2D-tilt-cross-double-slit.

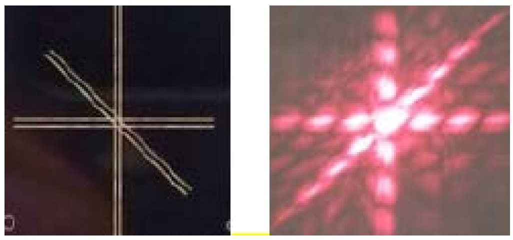

Figure 8. Cross-double-slit Experiment

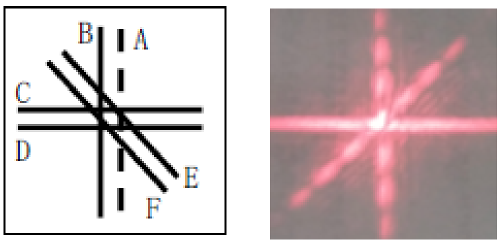

Figure 9. Which-way-cross-double-slit experiment

The tilt-double-slit has no reflection symmetry with respect to both vertical double-slit and horizontal double-slit. The interference pattern created by the tilt-double-slit has no reflection symmetry with respect to that created by vertical double-slit and horizontal double-slit. Photons passing through slit-C interfere with photons passing through its paired slit, slit-D, to create the interference pattern, but do not interfere with those photons passing through other slits, say slit-E and slit-F. How can photons make this "decision"?

Figure 9 shows the which-way-tilt-cross-double-slit experiment. We observed that: (1) The vertical double-slit-AB with slit-A blocked creates a horizontal pattern that shows particle nature of photon; (2) the double-slit-CD and double-slit-EF create interference patterns that show wave distribution of photons; thus (3) particle nature and wave distribution of photons coexist in the same experiment with the same apparatus, which clearly violate Bohr's complementarity principle.

Experiment-4 (Figure 11): Which-way experiments with 2D-multi-tilt-cross-double-slit.

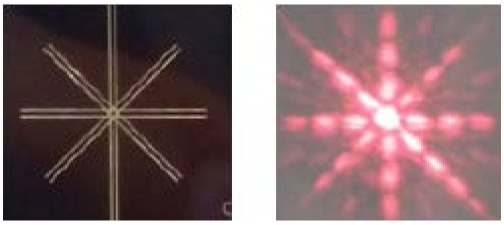

Figure 10. Cross-double-slit Experiment

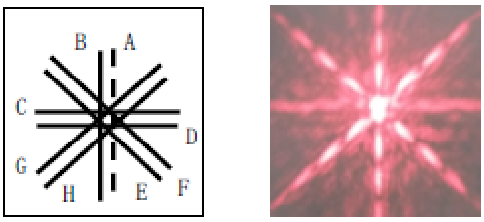

Figure 11. Which-way-cross-double-slit experiment

The 2D-multi-tilt-cross-double-slit (Figure 10 and Figure 11) consists of two set of cross-double-slit. One set of cross-double-slit rotates 45^0 with respective to another set of cross-double-slit.

Bohr's complementarity states that "Two complementary natures, wave and particle, of photons cannot both be observed or measured simultaneously."

The which-way-2D-multi-tile-cross-double-slit experiment-4 shows that when slit-A is blocked, the horizontal interference pattern disappears, which indicates the particle nature of photon, while other interference patterns, due to other double-slits, still exist. The conclusion is that the Bohr's Complementarity principle is violated.

4.2. Wave-Particle-Paradox

Now we need to interpret the complicated which-way-2D-cross-double-slit experimental results:

A. Without blocking a slit, photons pass through all of double-slits to create 2D-cross-interference patterns. But photons have to "remember" which slit they pass through to create the interference patterns accordingly;

B. Then blocking a slit. Before photons reaching the detection screen, they face several options:

(B1) When photons pass through a blocked slit, say slit A, photons should behave as *particle*;

(B2) When photons pass through slit B that is the slit A's paired slit, photons should behave as *particle*.

(B3) When photons pass through un-blocked double-slits, they should distribute as wave.

We refer to this situation as *Wave-Particle Paradox*.

5. Summary

Which-way-1D-double-slit experiment shows particle nature of photon and thus, confirms the complementarity principle. On the contrary, as shown in this article, the which-way-2D-cross-double-slit experiments show the coexistence of wave distribution and particle nature of photons in the same experiment with the same apparatus and thus, the complementarity principle is violated (Table 1).

Table 1. Comparison of 1D-double-slit and 2D-cross-double-slit experiments

	Young's 1D-double-slit experiments	2D-cross-double-slit experiments
Standard	Mystery of quantum world (Feynman)	Challenge standard interpretations of 1D-double-slit experiment
Which-way	Confirm Bohr's complementary principle	Challenge Bohr's complementary principle

Moreover, even we observe wave distribution, photons are always found to be absorbed at the detection screen at discrete points, as individual particles; the interference pattern appears via the varying density of these particle hits on the screen.

To summarize, photon's intrinsic nature is particle, while wave distribution of photons takes places only for special situations, such as in cross-double-slit experiment. In a situation of which-way-cross-double-slit experiment, particle nature and wave distribution coexist.

Thus, we conclude that the "particle nature" is intrinsic nature of photon, while the term "wave nature" is a "wave-like distribution", which is a consequence of movement of photon as particle.

The question is: How can photons adjust their behaviors simultaneously when passing through different slits in which-way-cross-double-slit correspondingly?

It is a challenge to consistently interpret those which-way-2D-cross-double-slit experiments. All of above experiments suggest that the which-way-2D-cross-double-slit experiments open a new door for re-studying basic quantum phenomena, such as wave-particle duality and the complementarity principle.

I am willing to provide slides of cross-double-slit (shown in Figure 4) to readers who are willing to DIY cross-double-slit experiments and contact me.

Appendix:

Photoelectric-which-way-cross-double-slit Thought-experiment

The regular interpretation of double-slit experiment contains a statement that before arriving a double-slit apparatus, photons behave as wave from the time of its emission to the time of its detection.

To test the statement, let's combine apparatus of which-way-cross-double-slit and apparatus of photoelectric effect. We propose an apparatus, denoted as Photoelectric-which-way-cross-double-slit apparatus (Figure 12). Both the board of cross-double-slit and the detection screen are made of photoelectric material (Figure 12). Where "Photoelectric material" implies any material and/or device that can register single photon. The source emits a beam of photons pointing to the photoelectric-cross-double-slit. The slit-A is covered, represented by dashed slit-A.

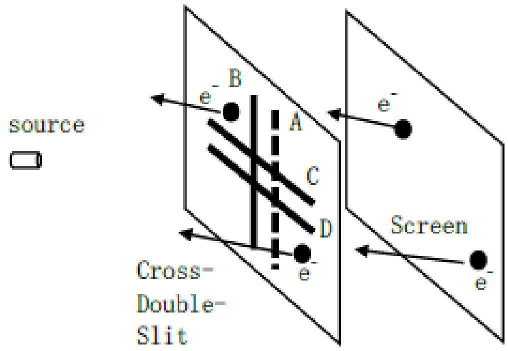

Figure 12. Photoelectric-which-way-Cross-Double-Slit Thought-Experiment

It is reasonable to expect that both the photoelectric effect and the phenomena of which-way-cross-double-slit would independently exist simultaneously.

Some of photons strikes on the photoelectric-board of cross-double-slit-ABCD. Electrons are ejected. Collecting and measuring those electrons disclose the particle-nature of photons, regardless the existence of narrow slit A that is covered, slit B, slit C and slit D on the board. Namely before passing through the cross-double-slit, photons behave as particle, not as wave.

Rest of photons passing through cross-double-slit-ABCD behaves mysteriously, that: (1) photons passing through double-slit-CD form interference distribution on photoelectric-detection-screen, regardless material of the detection-screen, and thus, considered as wave; (2) photons passing through slit-B behave as particle; (3) photons as particles knock electrons out of the photoelectric-detection-screen (a photoelectric effect again), regardless how photons distribute on photoelectric-detection-screen, and thus, considered as particle.

This is a paradox.

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