Cross-Double-Slit Experiment and Delayed-Choice-Cross-Double-Slit Experiment

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Abstract

We have performed cross-double-slit experiment and delayed-choice-cross-double-slit experiment, denoted as extended double-slit experiments. The cross-double-slit experiments show that the cross-double-slit apparatus creates not only two interference patterns, but also four cross-interference-patterns, which are created by two double-slit. The delayed-choice-cross-double-slit experiments disclose new phenomena: (1) photons behave as both wave and particle in the same experiment simultaneously, which violate Bohr's complementarity; (2) the cross-interference-pattern is created by one double-slit and one single-slit; (3) photons passing through the same slit behave as both wave and particle, referred it as the Wave-Particle-Paradox, which demands extensive study. We suggest to re-study wave-particle duality.

Key words: wave-particle duality, quantum mechanics, double-slits experiment, interference pattern, delayed-choice experiment

1. Introduction

In Young's double-slit experiments, photons create interference patterns, even emitting one photon at a time [1]. This result is interpreted as that each photon has arrived by both slits at the same time. Feynman stated that this wave-particle dual behavior contains the basic mystery of quantum mechanics [2]. The mechanism behind the law is unknown [3]. Utilizing only double-slit apparatus is not sufficient for understanding fully the wave-particle duality. Variety experiments have been proposed and performed, such as using entanglement photos [4], placing the light source on a satellite and measure on the ground [5]. The double-slit experiment has been performed with varying numbers of slits [6], such as multiple *parallel* slits. To test the interpretation, which-way-double-slit experiments have been proposed and performed [7]. The experimental result is that once which slit a photon passing through is determined, the wave-like interference pattern disappeared and the wave function is collapsed, namely the photon behaviors like a particle. It is interpreted as that two complementary natures, wave and particle, of photons cannot all be observed or measured simultaneously. Bohr called this either wave-like or particle-like behavior "complementarity" and stated that the type of measurement performed on a quantum system determines its behavior [8]. The operational definition of "wave/particle" stands for "ability/inability to create interference" [9].

Wheeler proposed delayed-choice experiments to decide whether a photon "senses" the experimental apparatus in the double-slit experiment and adjusts its behavior to fit [10].

Recently, for studying wave-particle duality further, the cross-double-slit apparatus is proposed [11]. In this article, we report the observations of the cross-double-slit, which-way-cross-double-slit and delayed-choice-cross-double-slit experiments.

2. Cross-Double-Slit Experiment

2.1. Review of Cross-Double-Slit Apparatus

The cross-double-slit apparatus contains a source (not shown), a slit wall with four slits, and a screen/detector. Where slits A and B are in z-direction, slits C and D are in y-direction. The photons travel in negative x-direction (Fig.1a).

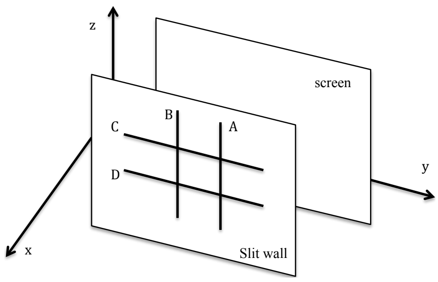

Fig. 1a Cross-Double-Slit Apparatus

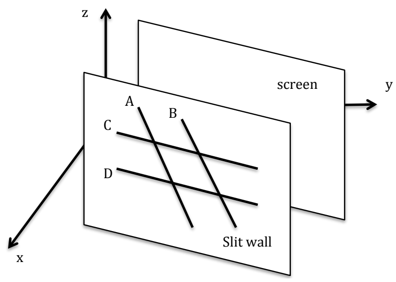

Fig. 1b Tilt-Cross-Double-Slit Apparatus

An alternative configuration: slits A and B are at an angle with slits C and D (Fig. 1b).

2.2. Cross-Double-Slit Experiment

Based on the results of regular double-slit experiment, one knew that slits A and B alone cause an interference patter in y-direction on the screen. Similarly, slits C and D alone cause an interference patter in z-direction. What pattern will the Cross-Double-Slit Experiment show?

We have performed the experiment and obtain the interesting and encourage results.

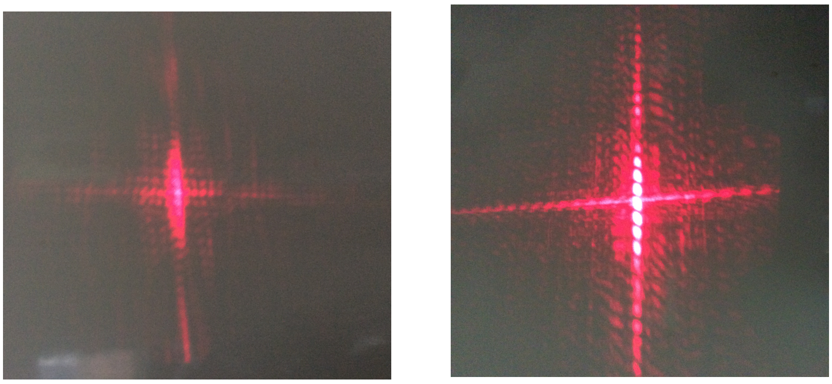

Fig. 2a Interference Patterns of Cross-Double-Slit Experiments

The observed patterns (Fig. 2a) are as predicted in [11]:

(A) The slits A and B cause the horizontal interference pattern, while slits C and D cause the vertical interference pattern. Two interference patterns are perpendicular to each other.

(B) There are some kinds of "interference patterns" as shown in First, Second, Third, and Fourth coordinate system quadrants respectively. We refer this kind of "interference patterns" as ***"Cross-Interference-Patterns".***

2.3. Tilt-Cross-Double-Slit Experiment

The observed pattern of the tilt-cross-double-slit experiment is shown in Fig. 2b.

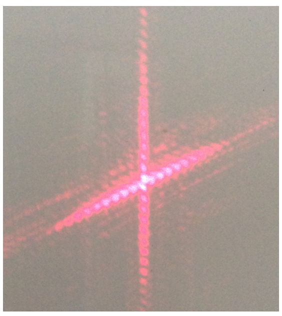

Fig. 2b Interference Patterns of Tilt-Cross-Double-Slit Experiments

(A) The slits A and B cause the tilted interference pattern, while slits C and D cause the vertical interference pattern. Two interference patterns are at an angle to each other.

(B) There is the cross-interference-pattern.

2.4. On "Cross-Interference-Pattern"

Now let's study what creates the cross-interference-pattern. For this aim, let's consider a cross-single-slit, which contains a vertical slit A and a horizontal slit C, as shown in Fig. 3a.

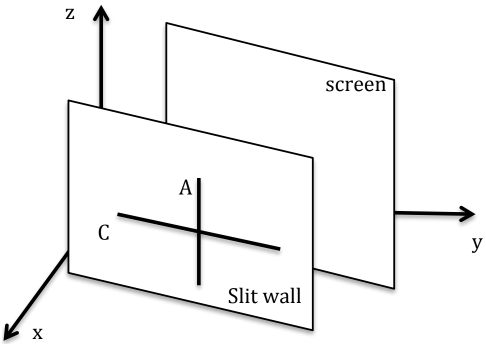

Fig. 3a Cross-Single-Slit

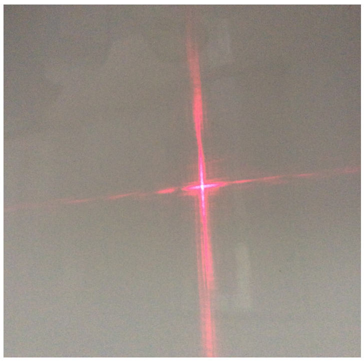

Fig. 3b Pattern of Cross-Single-Slit

This cross-single-slit apparatus creates a pattern as shown in Fig.3b.

Note there is neither interference pattern nor "Cross-Interference-Patterns", which implies that two perpendicular single slits A and C do not create interference-patterns.

Therefore we conclude that the "Cross-Interference-Pattern" is created by Cross-double-slit.

2.5. Interpretation

Now we face a difficult task that is to try to interpretation the experimental result.

For regular double-slit experiment, if we cover one slit at a time and measure the probability at the screen/detector, P_A is the probability of the wave from slit A (which is measured when slit B is blocked off) and P_B is the probability from slit B (when slit A is blocked). The wave functions ψ_A and ψ_B satisfy different boundary conditions. So, in a double slit experiment, the probability P_{AB} observed when both slits are open is certainly not the sum of P_A and P_B [12]. The discrepancy between P_{AB} and $P_A + P_B$ is due to a contribution from non-classical paths, and creates the "interference" of the two waves. The probability, ignoring the effects of non-classical paths, is

$$P_{AB} = (\psi_A + \psi_B)^2 = \psi_A^2 + \psi_B^2 + (\psi_A^* \psi_B + \psi_A \psi_B^*), \qquad (1)$$

The last term in Eq. 1, $(\psi_A^* \psi_B + \psi_A \psi_B^*)$, is the "interference term" [3].

In this article, we ignore the effect of non-classical paths. Following the same argument, when cross-double-slits A, B, C, and D are open, the probability amplitude for the photons landed on the screen/detector is the sum of the probability amplitudes for photons passing through each slit separately,

$$\psi = \psi_A + \psi_B + \psi_C + \psi_D, \tag{2}$$

then the probability is

$$P = |\psi|^2 = \psi_A^2 + \psi_B^2 + \psi_C^2 + \psi_D^2 + (\psi_A^*\psi_B + \psi_A\psi_B^*) + (\psi_C^*\psi_D + \psi_C\psi_D^*) +$$

$$+(\psi_A^*\psi_C + \psi_A\psi_C^*) + (\psi_A^*\psi_D + \psi_A\psi_D^*) + (\psi_B^*\psi_C + \psi_B\psi_C^*) + (\psi_B^*\psi_D + \psi_B\psi_D^*). \tag{3}$$

where

$(\psi_A^*\psi_B + \psi_A\psi_B^*)$ represents the interference term created by the slits A and B;

$(\psi_C^*\psi_D + \psi_C\psi_D^*)$ represents the interference term created by the slits C and D;

$(\psi_A^*\psi_C + \psi_A\psi_C^*)$ represents the cross-interference term created by the slits A and C;

$(\psi_A^*\psi_D + \psi_A\psi_D^*)$ represents the cross-interference term created by the slits A and D;

$(\psi_B^*\psi_C + \psi_B\psi_C^*)$ represents the cross-interference term created by the slits B and C;

$(\psi_B^*\psi_D + \psi_B\psi_D^*)$ represents the cross-interference term created by the slits B and D.

Following the regular interpretation of regular double-slit experiments, we interpret that a photon passes through 4 slits simultaneously, and create the interference patterns.

Note this interpretation is not applicable to the which-way-cross-double-slit and delayed-choice-cross-double-slit experiments as shown below.

3. Which-Way-Cross-Double-Slit and Delayed-Choice-Cross-Double-Slit Experiment

3.1. Experiment and Observation

It is known that an observation of which slit the photon passed through causes the interference pattern disappeared, namely the observation converts the wave-like behavior to particle-like behavior. If the observer is placed before the slit wall, it is referred as which-way-cross-double-slit experiment, while the observer is placed behind the slit wall and is on and off, then it is referred as delayed-choice-cross-double-slit experiment.

Now let's perform delayed-choice-cross-double-slit experiment by putting an observer behind one of slits, say slit A, which is represented by dotted line A in Fig. 4, to observe photons passing through slit A.

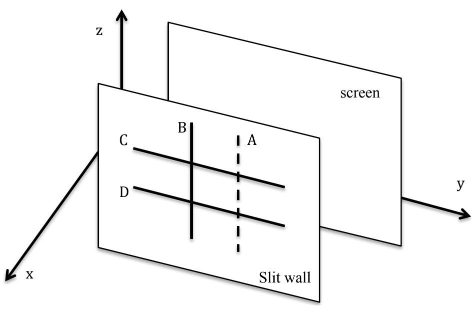

Fig. 4 Delayed-Choice-Cross-Double-Slit Experiment

Without the observation, one obtains interference patterns as show in Fig. 2a and 2b.

After a photon leave the source, before landing on the screen/detector, turn on the observation, we obtain the pattern as shown in Fig. 5.

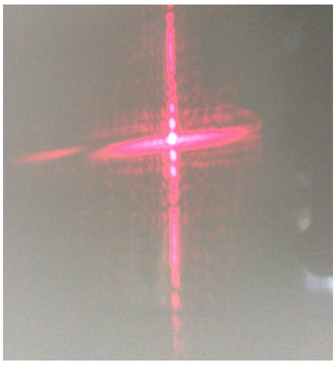

Fig. 5 Interference pattern of Delayed-Choice-Cross-Double-Slit Experiment

Fig. 5 shows the following:

(1) The horizontal interference pattern due to the slits B and A *disappeared*, since photons passing through slit A are observed, which implies that photons passing through slits A and B behave as particles.

(2) There is still vertical interference pattern due to slits C and D, which implies that photons passing through slits C and D behave as wave.

(3) There are still "Cross-interference-pattern" in all of four coordinate system quadrants, caused by slits B and C and by slits B and D, which implies that photons pass through slit B, slit C, and slit D as wave.

3.2. Mathematical Interpretation

Mathematically, when slits C and D are "open", slit B is "open" and "close", and slit A is "closed", the probability amplitude for the photons landed on the screen/detector is the sum of the probability amplitudes for photons passing through each slit separately,

$$\psi = \psi_B + \psi_C + \psi_D, \tag{4}$$

$$\psi_A = 0. \tag{5}$$

Then the probability is

$$P = \psi_B^2 + \psi_C^2 + \psi_D^2 + (\psi_C^*\psi_D + \psi_C\psi_D^*) + (\psi_B^*\psi_C + \psi_B\psi_C^*) + (\psi_B^*\psi_D + \psi_B\psi_D^*). \tag{6}$$

Where

$(\psi_C^*\psi_D + \psi_C\psi_D^*)$ represents the interference term created by the slits C and D;

$(\psi_B^*\psi_C + \psi_B\psi_C^*)$ represents the cross-interference term created by the slits B and C;

$(\psi_B^*\psi_D + \psi_B\psi_D^*)$ represents the cross-interference term created by the slits B and D.

4. Wave-Particle-Paradox

Now we face a tremendous difficult task that is to try to interpret the experimental result, since much more complicated situations:

(1) a photon is emitted, if there is no observer, it can pass through each of slits A, B, C, D to create two interference patterns and four cross-interference-patterns. But the photon has to "remember" that it passes through slits A and B to create the horizontal interference pattern; it passes through slits C and D to create the vertical interference pattern; it passes through slits A and C, slits A and D, slit B and C, and Slits B and D to create the cross-interference-patterns;
(2) then turn on the observation, before the photon reaching the screen/detector, it faces several options:
    (A) when the photon passes through slit A, it has to behave as a *particle*;
    (B) when the photon passes through slit B, it has trouble: first it needs to behave as a *particle* so that the interference pattern created by slits A and B disappeared; at the same time, it needs to behave as a *wave* so that the cross-interference-patterns created by slits B and C and by slits B and D exist;
    (C) when the photon passes through slits C and D, it needs to behave as *wave*, so that the interference pattern retains.

The severe question is: how can a photon adjust its behaviors simultaneously when pass through different slits accordingly?

The wave-like and particle-like behaviors of photons coexist in the same experiment with the same experimental apparatus, which suggest us to re-study the wave-particle duality and complementarity.

Photons, as wave, pass through slits B, C and D to create the Cross-interference-pattern, and pass through slits C and D to create the interference-pattern; while photons pass through slits A and B as particles. We denote it as "*Wave-Particle-Paradox"*, which challenges us: (1) how can photons passing through the same slit B behave as both wave and particle? (2) how can photons passing through the slits A and B behave as wave when it is not observed, photons passing through the slits A and B behave as particle when it is observed; while photons passing through the slits C and D behave always as wave regardless with or without observation at slit A?

5. Further Experiment.

For further study, the same experiments should be done with photons emitted one at a time to determine whether a photon is passing through 4 slits simultaneously; and whether there are same interference patterns and cross-interference-patterns. Furthermore, do the same experiments with electrons.

6. Conclusion

We have performed two experiments, cross-double-slits and delayed-choice-cross-double-slit experiments. The observations: (1) show that cross-double-slit causes not only two interference patterns, but also four cross-interference-pattern; (2) the cross-interference-pattern is generated either between two double-slit or between one double-slit and one single slit; (3) disclose a new feature of photons, called as the Wave-Particle-Paradox, which demands extensive study; and (3) suggest to re-study wave-particle duality.

Reference

(1) W. Rueckner and J. Peidle, Am. J. of Phy. **81**, 951 (2013).

(2) R. P. Feynman, R. B. Leighton, and M. Sands, The Feynman Lectures on Physics (Addison-Wesley, Reading, 1966), Vol. 3.

(3) M. Gottlied and R. Pfeiffer, www.feynmanlectures.caltech.edu.

(4) Y. H. Kim, et al., arXiv:quant-ph/9903047 (1999).
F. Kaiser, et al., Science 02 Nov (2012).

(5) F. Vedovato, et al., Science advances 25 Oct (2017).

(6) S. Eibenberger, et al., Physical Chemistry 15 (35) (2013).

(7) J. Q. Quach, Phys. Rev. A 95, 042129 (2017).
S. Frabboni, G. Gazzadi, and G. Pozzi, Appl. Phys. L. 97, 263101 (2010).

(8) N. Bohr, in Quantum Theory and Measurement, J.A. Wheeler and W.H. Zurek, Eds. (Princeton Univ. Press, Princeton, NJ, 1984), pp. 9–49.

(9) G. Greenstein and A.G. Zajonc, The Quantum Challenge: Modern Research on the Foundations of Quantum Mechanics (Jones and Bartlett, Boston, 1997).
J. Baggott, “The Quantum Story: A History in”. Oxford University Press (2011).
R. Ionicioiu and D.R. Terno, Phys. Rev. Lett. 107, 230406 (2011).

(10) A. R. Marlow, Editor, “Mathematical Foundations of Quantum Theory”, (Academic Press, 1978).

(11) Hui Peng, www.open-science-repository.com/physics-45011872.html (2019).

(12) R. Sawant, et al., Physical Review Letters, 113(12), (2014).