New Interpretation and Verification Experiment of Single-photon Double-slit Interference

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[Abstract] A light wave is the emission wave of photons, and its propagation in a vacuum does not require any medium. Based on wave-particle duality of light, this paper proposes that the interference of light is caused by the wave characteristics of a single photon itself. **A light wave is the cumulative expression of the individual movement of a single photon particle with the wave characteristics at different times.** The double-slit interference of light requires neither two wave sources nor multiple photons to participate at the same time. Therefore, in the single photon double-slit interference experiment, a single photon can pass through one of the two slits in turn to achieve double-slit interference. There is no superposition principle in the single photon double-slit interference experiment, and a single photon cannot pass through two slits at the same time. Furthermore, a verification experiment to check the superposition principle of single photon double-slit interference is presented. A light shield is used to block one of two slits in turn to ensure that each single photon can only pass through one of the two slits separately. The verification experiment of single photon double-slit interference will expand people's understanding of the quantum world, and it is a new challenge to the superposition principle, Heisenberg uncertainty principle and quantum entanglement.

[Keywords] photoelectric effect, wave-particle duality, wave characteristics, particle characteristics, light wave, photon, single-photon double-slit interference, superposition principle.

1. Introduction

In 1690, Huygens proposed the wave principle of light, but this theory was soon replaced by Newton’s particle theory of light, which stated that light was composed of tiny particles.

In the early 19th century, Thomas Young’s light wave double-slit interference experiment provided a new experimental basis for Huygens’ wave theory of light. In 1865, Maxwell introduced the “displacement current” hypothesis and theoretically predicted that light was “an electromagnetic wave”. Then Huygens’ wave theory of light was re-accepted.

In 1905, Einstein solved the riddle of the photoelectric effect and established the wave-particle duality of light. In 1924, De Broglie put forward the “material wave” hypothesis, which stated that all matter has wave-particle duality. According to this hypothesis, electrons also have wave characteristics such as interference and diffraction. This was later confirmed by electron diffraction experiments.

When two strong beams of light cross vertically, photons do not collide and emit outward from the beams. This shows that the photons in the beam are independent of each other, and the volume of a photon itself is relatively very small compared to the space among photons. Modern technology cannot measure the diameter of photons, but the diameter of an electron is about 10^{-13} nm, and the diameter of a photon must be much smaller than that of an electron. Photons are energy particles with extremely small diameters.

Photons have wave-particle duality, they have both particle characteristics and wave characteristics.

2. Single-photon double-slit interference experiment and superposition principle

The double-slit interference experiment is the most important experiment for providing proof of light wave characteristics. Without losing generality, a laser source S is set to emit a parallel laser beam that passes through two parallel slits S_1 and S_2. The parallel beam emitted by S forms a pair of coherent light sources with the same initial phase and the same intensity at double slits S_1 and S_2. The coherent light causes detection screen E behind the double slits to display bright and dark interference fringes. The experimental device is shown in Figure 3.1.

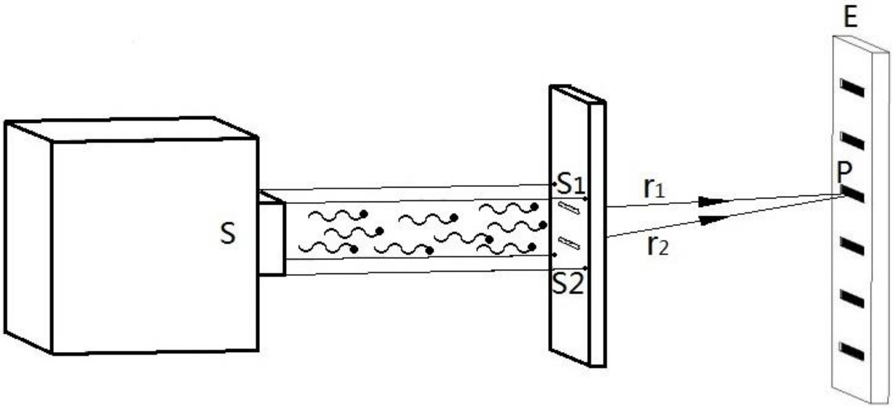

Fig. 3.1 Light beam double-slit interference experiment device

With the assumption that the power of the laser source S is 1.0 w, the cross-section size of the beam is 1 mm x 6 mm, the cross-section size of the double-slits S1 and S2 is 0.02 mm x 4 mm, and the photon wavelength λ= 570 nm, with the frequency of $\gamma = 5.26 \times 10^{14}$ Hz. The energy of one photon is:

$$E_\gamma = h\gamma$$

$$= 6.626 \times 10^{-34} \times 5.26 \times 10^{14},$$

$$E_\gamma = 3.487 \times 10^{-19} \text{ J}.$$

The number of photons emitted by a 1.0-w laser source in 1 second is:

$$N_\gamma = 1/ E_\gamma$$

$$=1/ (3.487 \times 10^{-19}),$$

$$N_\gamma = 2.868 \times 10^{18}.$$

The number of photons emitted through the 0.02 mm x 4 mm slit in 1 second is:

$$n_\gamma = N_\gamma (0.02 \times 4) / (1 \times 6)$$

$$= 2.868 \times 10^{18} \times 0.00333,$$

$$n_\gamma = 9.56 \times 10^{15}.$$

People's visual retention time for light is 0.05 seconds to 0.2 seconds, and the visual retention time is set to 0.1 seconds. The number of photons passing through two 0.02 mm x 4 mm slits in 0.1 seconds is:

$$n_{\gamma 0} = 1.912 \times 10^{15}. \qquad (3\text{-}1)$$

In quantum mechanics, the single photon double-slit interference experiment is one of the most important fundamental experiments, and its most mysterious and controversial aspect is determining which of the slits S_1 and S_2 a single photon passes through to the detection screen E. Based on the particle characteristics and wave characteristics of photons, we further discuss the single-photon double-slit interference experiment below.

As shown in Figure 3.2, the laser source S is set to emit one photon at a time. The wavelength of a photon is λ=570 nm and the cross-section size of the double-slits S_1 and S_2 is 0.02 mm x 4 mm, which is the same as that of the experiment illustrated in Figure 3.1. Without losing generality, letting the laser source S emit a photon every 1 pico-second (10^{12} photons are emitted in 1 second), the photons pass through the double slits S_1 and S_2 in turn via different symmetrical paths. The photons passing through slit S_1 are p_1 (i) { i=1,3,5,7...}, and one photon p_1 (i) passes through slit S_1 every 2 pico-seconds. The photons passing through slit S_2 are p_2 (j) {j=2,4,6,8...}, and one photon p_2 (j) passes through slit S_2 every 2 pico-seconds. The initial phases of photons p_1 (i) and p_2 (j) at the double-slit S_1 and S_2 are the same.

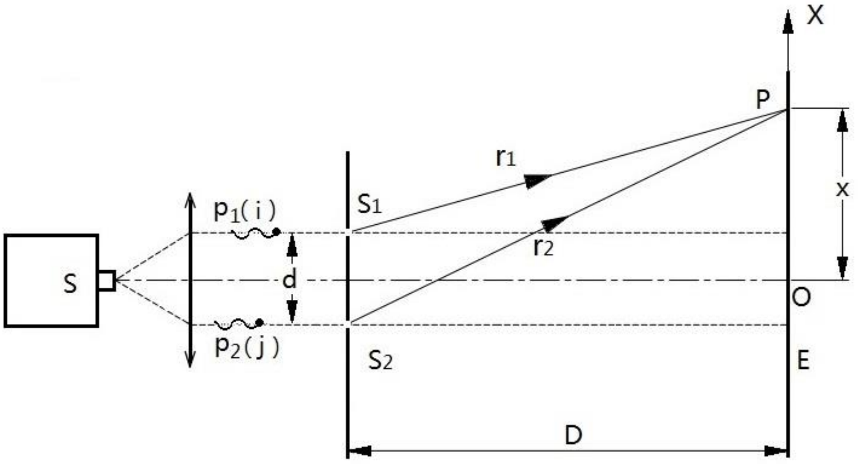

Fig. 3.2 Single photon double-slit interference experiment

It is assumed that the distance between S_1 and S_2 is d and the distance between the double-slit screen and the detection screen E is D. Taking O as the origin, the coordinate axis X is established, a point P (OP=x) on the X axis is selected, and the distances from point P to the double slits S_1 and S_2 are r_1 and r_2, respectively. The optical path difference of photons p_1 (i) and p_2 (j) from S_1 and S_2 to point P is

$$\Delta r = r_2 - r_1. \qquad (3\text{-}2)$$

According to Figure 3-2,

$$r_1^2 = D^2 + (x - d/2)^2; \qquad r_2^2 = D^2 + (x + d/2)^2.$$

Therefore,

$$r_2^2 - r_1^2 = (r_2 - r_1)(r_2 + r_1) = 2\,x\,d. \quad (3\text{-}3)$$

Because $D \gg d$ and $r_2 + r_1 \approx 2D$, according to Equations (3-2) and (3-3):

$$\Delta r = r_2 - r_1 = x\,d/D.$$

Assuming that the wavelength of photons $p_1(i)$ and $p_2(j)$ is λ, the conditions for the interference enhancement are:

$$\Delta r = x\,d/D = k\lambda.$$

That is,

$$x = k(D/d)\lambda,\ k=0, \pm 1, \pm 2, \ldots$$

The positions where the interference between photons $p_1(i)$ and $p_2(j)$ is strengthened are the bright stripes of light. When k=0, then x=0; that is, the origin O is the center of the bright stripe, which is called the central bright stripe. When $k=\pm 1, \pm 2$, then $x=\pm(D/d)\lambda, \pm 2(D/d)\lambda$. The corresponding bright stripes are the first-level bright stripe and the second-level bright stripe.

If the wavelength of photons $p_1(i)$ and $p_2(j)$ is λ, the conditions for the interference reduction are:

$$\Delta r = x\,d/D = (2k+1)(\lambda/2).$$

That is,

$$x = (2k+1)(D/2d)\lambda,\ k=0, \pm 1, \pm 2, \ldots$$

When $k= 0, \pm 1$, then $x=\pm(D/2d)\lambda, \pm(3D/2d)\lambda$. The corresponding dark stripes are the zero-level dark stripe and the first-level dark stripe. The bright and dark stripes are arranged at intervals, and the distance between the centers of two adjacent bright stripes (or dark stripes) is:

$$\Delta x = (D/d)\lambda.$$

According to Equation (3-1), the number of photons to be emitted by the laser source S is $n_{\gamma 0} = 1.912 \times 10^{15}$, while the laser source S can emit 10^{12} photons per second. Therefore, the time required for this experiment is:

$$T = 1.912 \times 10^{15}/10^{12},$$

$$T = 1912 \text{ seconds}.$$

The experimental results show that the interference fringes obtained on the detection screen E of the single photon double-slit interference experiment in Figure 3.2 are the same as those obtained in the parallel beam double-slit interference experiment in Figure 3.1. According to the wave interference theory, the interference fringes come from the interference superposition between two wave sources in the two slits. How does a single photon interfere?

Based on the superposition principle, modern quantum mechanics believes that a single photon simultaneously passes through slit S_1 and slit S_2, forming two wave sources and achieving interference fringes on the detection screen E. For the single photon double-slit interference in Figure 3.2, according to the superposition principle of quantum mechanics, when a single photon $p_1(i)$ passes through slit S_1, it generates a superposition effect, and $p_1(i)$ passes through slit S_1 and slit S_2 at the same time. Similarly, when a single photon $p_2(j)$ passes through slit S_2, it generates a superposition effect, and $p_2(j)$ passes through slits S_2 and slit S_1 at the same time.

3. New interpretation and verification experiment of the single-photon double-slit Interference

A mechanical wave is the propagation process of mechanical vibration in a medium. It can be seen that a wave source and an elastic medium are two necessary conditions for mechanical wave generation. For example, when a person speaks, his vocal cords vibrate. The vocal cord is the wave source and the air is the medium for transmitting sound. A mechanical wave is the **instantaneous expression** of the collective movement of many particles participating in vibration **at the same time.** For example, a sound wave is the instantaneous expression of the collective movement of many air molecular particles.

A light wave is the emission wave of light particles, and its propagation in a vacuum does not require any medium. The interference of light is caused by the wave characteristics of a single photon itself. A light wave is the **cumulative expression** of the individual movement of a single photon particle with the wave characteristics **at different times.** The double-slit interference of light requires neither two wave sources nor multiple photons to participate at the same time. Therefore, in the single photon double-slit interference experiment above, a single photon passes through one of the two slits in turn to achieve double-slit interference. There is no superposition principle in the single photon double-slit interference experiment, and a single photon cannot pass through two slits at the same time

In order to verify that there is no superposition principle in the single photon double-slit experiment, and ensure that a single photon passes through one of two slits in turn. We make the following improvements to the experiment shown in Figure 3.2. First, the light shield B_2 is used to block slit S_2, and only slit S_1 is opened. The laser source S emits a photon every 1 pico-second that can only pass through slit S_1. The laser source S emits 9.56 $\times10^{14}$ photons to slit S_1 in turn, as shown in Figure 3.3A.

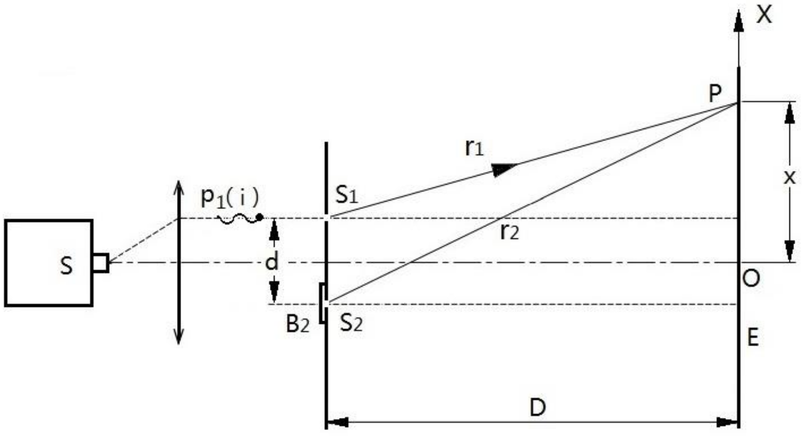

Fig. 3.3A Single photon double-slit interference (S_2 blocked)

Then slit S_2 is opened and slit S_1 is blocked with the light shield B_1. The laser source S emits a photon every 1 pico-second, and the photon can only pass through slit S_2. The laser source S emits 9.56 $\times 10^{14}$ photons to slit S_2 in turn, as shown in Figure 3.3B.

Check the results of the experiments in Figure 3.3A and Figure 3.3B. If the interference fringes on the detection screen E are the same as those in the experiment of Figure 3.2, then a single photon can pass through one of the two slits in turn to achieve the interference fringes in the single photon double-slit interference experiment. There is no superposition principle in the single photon double-slit interference experiment, and a single photon cannot pass through two slits at the same time

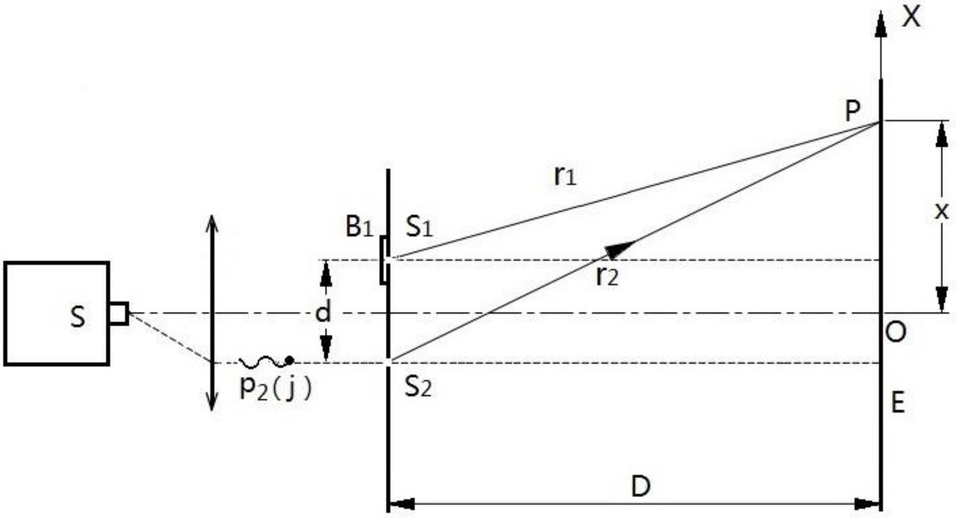

Figure 3.3B Single photon double-slit interference (S_1 blocked)

For the experiments shown in Figure 3.2, Figure 3.3A and Figure 3.3B, the existing single-photon double-slit interference equipment in the laboratory can be used. Step one: According to the conventional process, slit S_1 and slit S_2 are opened, a single photon double slit interference experiment is conducted, the interference fringes obtained on the detection screen E are saved, and the experiment operation time T_S is recorded. Step two: First, slit S_1 is blocked with a light shield, slit S_2 is opened, and the same experimental process and operation time T_S in step one are used to conduct the single-photon double-slit interference experiment. Then slit S_2 is blocked with a light shield and slit S_1 is opened, and the same experimental process and operation time T_S in step one are used to conduct the single-photon double-slit interference experiment again. The interference fringes obtained from step two on detection screen E are compared with the interference fringes obtained from step one on detection screen E. If the interference fringes are the same, then there is no superposition principle in the single photon double-slit interference experiment; that is, a single photon cannot pass through slit S_1 and slit S_2 at the same time.

For the verification experiments showed in Figure 3.3A and Figure 3.3B, a simpler method is to set a light barrier B between the two slits S_1 and S_2 of the single photon double-slit interference device to ensure that a single photon can only pass through one slit, as shown in Figure 3.4.

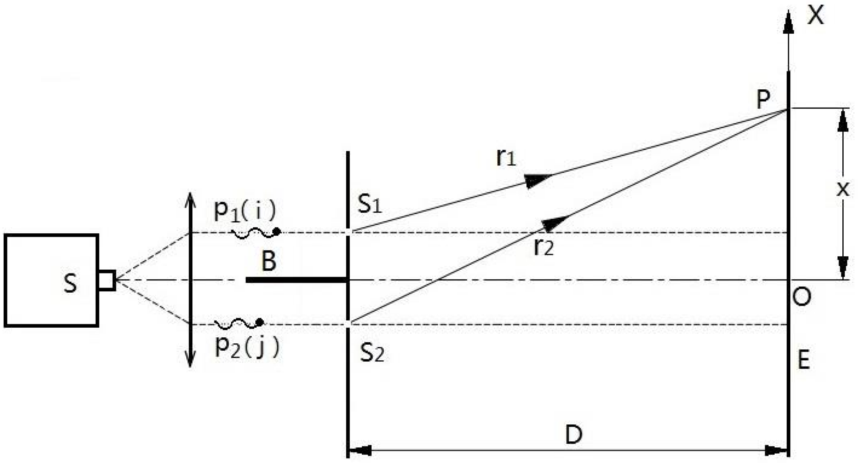

Figure 3.4 Single photon double-slit interference device with a light barrier

The single-photon double-slit interference experiments in Figure 3.2, Figure 3.3A, Figure 3.3B, and Figure 3.4 are also applicable to other microscopic particles such as electrons.

4. Conclusion

Based on the photoelectric effect, Einstein proposed and established the wave-particle duality of light. A light wave is the emission wave of light particles, and its propagation in a vacuum does not require any medium. This paper proposes the interference of light is caused by the wave characteristics of a single photon itself. **A light wave is the cumulative expression of the individual movement of a single photon particle with the wave characteristics at different times.** The double-slit interference of light requires neither two wave sources nor multiple photons to participate at the same time. Therefore, in the single photon double-slit interference experiment, a single photon passes through one of the two slits in turn to achieve double-slit interference. There is no superposition principle in the single photon double-slit interference experiment, and a single photon cannot pass through two slits at the same time.

Furthermore, a verification experiment to check the superposition principle of single photon double-slit interference is presented. A light shield is used to block one of two slits in turn to ensure that each single photon can only pass through one of the two slits separately. The verification experiment of single photon double-slit interference will expand people's understanding of the quantum world, and it is a new challenge to the superposition principle, Heisenberg uncertainty principle and quantum entanglement.

Availability of Data and Materials:

All data generated or analysed during this study are included in this published article and its supplementary information files.

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