# Observation of photon movement near Young's double-slit

Kazufumi Sakai

TPORD (Optical Science)
Hoei-Haitu 1-11, Yabu-machi 74-11
Tosu-city, SAGA 841-0055 JAPAN

*Corresponding author E-mail*: ksakai@phj.sakura.ne.jp

**Abstract**

The quantum interference phenomenon was observed in Young's double-slit experiment using a single photon, and then, the validity of quantum mechanics was demonstrated. However, the reason these fringes appear has not been completely explained yet because photon motion has not been investigated in detail. We found a method to observe the motion of photons using the properties of optical fibers and showed vector diagrams of the photon motion near the double-slit. The photons gradually changed their direction while intersecting and formed interference fringes. In addition, utilizing the mode property of the fiber, we observed fringes at its output end, even when one of the two interfering waves could not transmit through the fiber.

***Keywords*:** de Broglie-Bohm interpretation, standard quantum theory, photon trajectory, photon movement, interference phenomenon

## 1. Introduction

One of the interesting mysteries in modern physics is the quantum interference phenomenon. Quantum interference experiments using double-slits best represent the strange behavior of particles in the quantum world due to their simplicity. However, the behavior of the photons in the double-slit experiment remains ambiguous. This mysterious quantum phenomenon is demonstrated by a single photon [1] and explained by standard interpretations (i.e., the Copenhagen interpretation), which involving the duality of particles and waves, the superposition principle [2], and the collapse of wave functions [3]. In addition, deterministic views, such as the interpretation of the de Broglie–Bohm theory [4,5], are an attempt to explain quantum interference while emphasizing well-defined trajectories [6]. The de Broglie–Bohm theory calculates the trajectory using two main equations: the continuity equation and the quantum Hamilton–Jacobi equation. One important feature of Bohmian trajectories is that the trajectories do not cross. This feature is a consequence of the single-valued nature of the field equation [7]. In the de Broglie–Bohm interpretation, the number of measured particles is proportional to the probability density of standard quantum mechanics. Therefore, simply measuring the particle distribution cannot be distinguished from standard quantum mechanics. Recently, Kocsis et al. measured the photon trajectories using weak-measurements and showed that they were equivalent to the trajectories predicted by the de Broglie–Bohm theory [8].

We have performed experiments that can determine which photon has passed through Young's double-slit [9], experiments that show the wave packet does not collapse [10], experiments on trajectories of intersecting photons [13], and so on [11,12]. In this paper, we report measurements of the photon movement and interference fringes near the double-slit using a single-mode optical fiber (SMF) and a multi-mode optical fiber (MMF).

In Chapter 2, utilizing the transmission properties of SMF, which is sensitive to the incident angle, we show that the interference effect was confirmed at the output end of the fiber, even when one of the two light waves could not pass through the optical fiber. The reason we could observe the interference effect when only one light wave could pass through the fiber is unknown. In Chapter 3, we explain a method to measure the direction of the photon motion near a double-slit using an MMF and show a vector diagram of photon movement. The results show that unlike Bohmian trajectories, the photons move straight while intersecting, gradually change their direction, and form interference fringes.

## 2. Interference fringes measured by SMF

Figure 1 shows an apparatus to observe interference fringes using an SMF. Laser light (635 nm, 1 mW) passes through a polarizing plate in a 45-degree polarization direction, and then enters a double-slit (200 μm intervals). The SMF (core diameter: 9.5 μm) inclined approximately 1 degree (θ) to the optical axis was arranged at a position approximately 9 mm from the double-slit. The light intensity was measured by a charge-coupled device (CCD) while scanning the optical fiber in the $x$-axis direction.

Since an SMF is an optical fiber that can transmit in only a specific mode, the intensity of transmitted light is sensitive to the incident angle. Figure 2 shows the correlation of transmitted light intensity for the incident angle on the SMF used in the experiment. Light is hardly transmitted when the incident angle is 2.0 degrees or more. The following experiments were performed using this property. First, the S2 slit in Fig. 1 was closed, and the S1 slit was opened (i.e., single slit); and the intensity distribution was measured in the $x$-axis direction (Fig. 3). Since the SMF was tilted, light could barely be measured in a region where $x$ was 150 μm or greater (region B in Fig. 3). It should be noted here that a light wave existed at the incident surface of the SMF due to the diffraction of the slit. Next, both slits were opened, and the same area was scanned. Since the interference fringes are formed by the superposition of two light waves, the interference fringes could not be measured at the CCD position. However, clear interference fringes were observed as shown in Fig. 3.

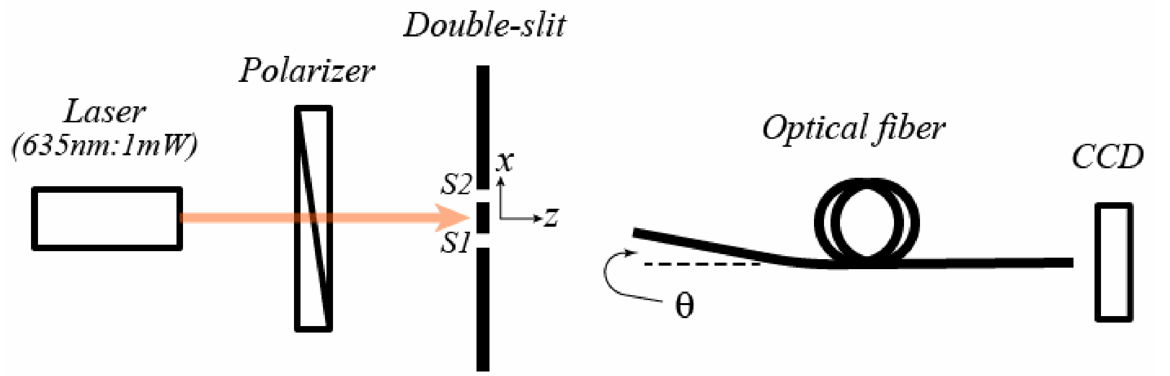


Fig. 1 Apparatus to observe interference fringes using an optical fiber. The laser beam passes through a polarizing plate (45 degrees) and a double-slit to form interference fringes. The interfering light enters an optical fiber (inclination θ) and is measured by a CCD placed at the end. The optical fiber is scanned in the *x* and *z* directions by motorized stages to obtain an intensity distribution.

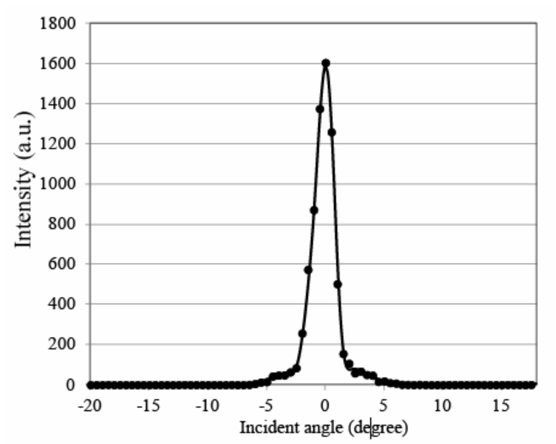


Fig. 2 Correlation of the incident angle and transmitted light of a single-mode optical fiber.

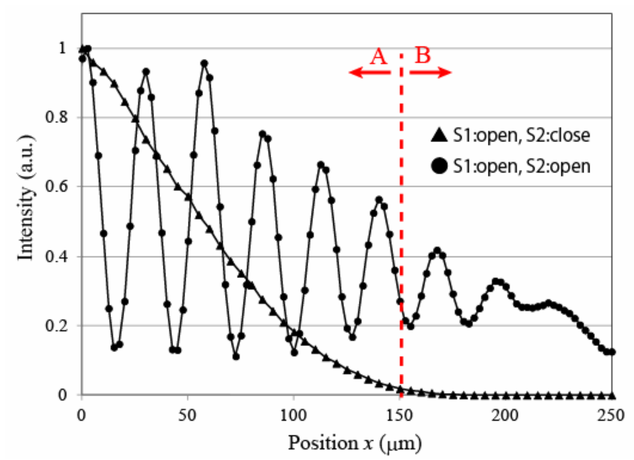


Fig. 3 Intensity distribution of light passing through a single slit and double-slit. The intensity was observed with a CCD placed at the end of the optical fiber. In the case of a single slit, diffracted waves were hardly observed where x was 150 μm or greater (region B), but when both slits were opened, interference fringes were observed.

Figure 4 shows a schematic diagram of this experiment. The red light wave entered the optical fiber but rapidly attenuated in the optical fiber due to a larger incident angle (mode mismatch). The blue light wave propagated through the optical fiber and was detected by the CCD at its output end. It is well known that if two beams cross and then leave, they will not be affected by the other light wave. With this in mind, we considered the experimental results in Fig. 1 with standard quantum mechanics. Assuming that the wave functions of the light wave output from the two slits are $f$ and $g$, the wave function immediately before entering the optical fiber can be expressed by $f(x) + g(x)$. In addition, since $f(x)$ cannot be transmitted, the wave function at the outgoing end is $g'(x)$ ($g'$ considers reflection and attenuation in the optical fiber). The interference effect should not be observed in the CCD because interference occurs with the superposition of two or more wave functions.

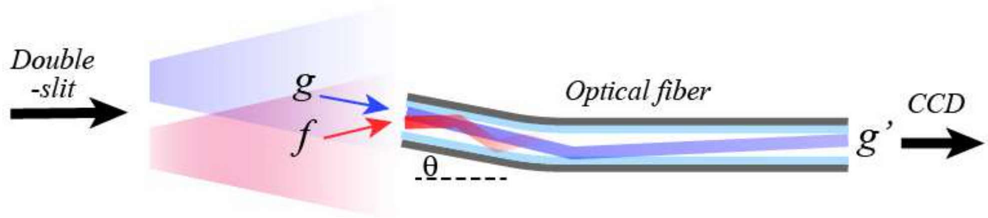


Fig. 4 Schematic diagram of the incident angle and propagation of light in the optical fiber. The light waves $f$ and $g$ emitted from the respective slits are superposed and enter the fiber, but $f$ does not match the mode of the optical fiber, so it decays rapidly in the optical fiber. Although the light wave detected by the CCD is $g'$, the interference effect is observed.

In contrast, assuming that particle and wave properties are independent, the experimental results can be easily interpreted. Immediately before the light enters the optical fiber, there are some photons according to the probability density distribution calculated from $f(x) + g(x)$, and some of the photons enter the optical fiber. The incident photons and light $g'(x)$ wave are guided to its output end and detected by the CCD. Therefore, the interference fringes are determined by the probability density at the entrance surface of the optical fiber independently of the wave function at the fiber end. It should be noted here that the energy of the $g'$ wave must be zero.

In this experiment, since the wave function on the incident surface of the fiber is a superposition of two wave functions ($f + g$), it cannot be determined which slit the detected photon has passed. Therefore, the detected photon may be a photon in the light-wave $f$. It is interesting to note that even if the light wave cannot pass through the fiber (mode mismatch), the photon may still be detectable.

### 3. Photon motion near the double-slit

The configuration of the apparatus to measure the momentum of photons was the same as that in Fig. 1. Laser light (635 nm, 1 mW) passed through a polarizing plate in a 45-degree polarization direction and then entered a double-slit (100 μm interval). The light wave from the double-slit was captured by an MMF (core diameter of 50 μm; optical fiber for energy transmission) inclined approximately 9 degrees to the optical axis of the laser. The optical fiber was scanned in the $x$-axis and $z$-axis directions by a motorized stage ($z$ = 0 to 16 mm, $x$ = −200 μm to 200 μm), and the transmitted light was observed with the CCD. Since the MMF was in multi-mode, many modes could propagate in the core of the fiber. When a light wave entered the MMF obliquely, a circular image was observed on the CCD, as shown in Fig. 5(a). When the distance between the fiber surface and the CCD was fixed and the incident angle of the light was changed, the radius of the circle continuously changed. The peak position (the radius of the circle) was obtained from the light intensity distribution to the distance from the center of the circle (Fig. 5(b)), and then, the correlation between the radius and the incident angle was obtained (Fig. 5(c)). The radius of the circle varied linearly with the incident angle. When light entered from two directions, two peaks were obtained, as shown in Fig. 5(d). Each peak position and amplitude can be calculated by a fitting curve of a combination of multiple Gaussian functions.

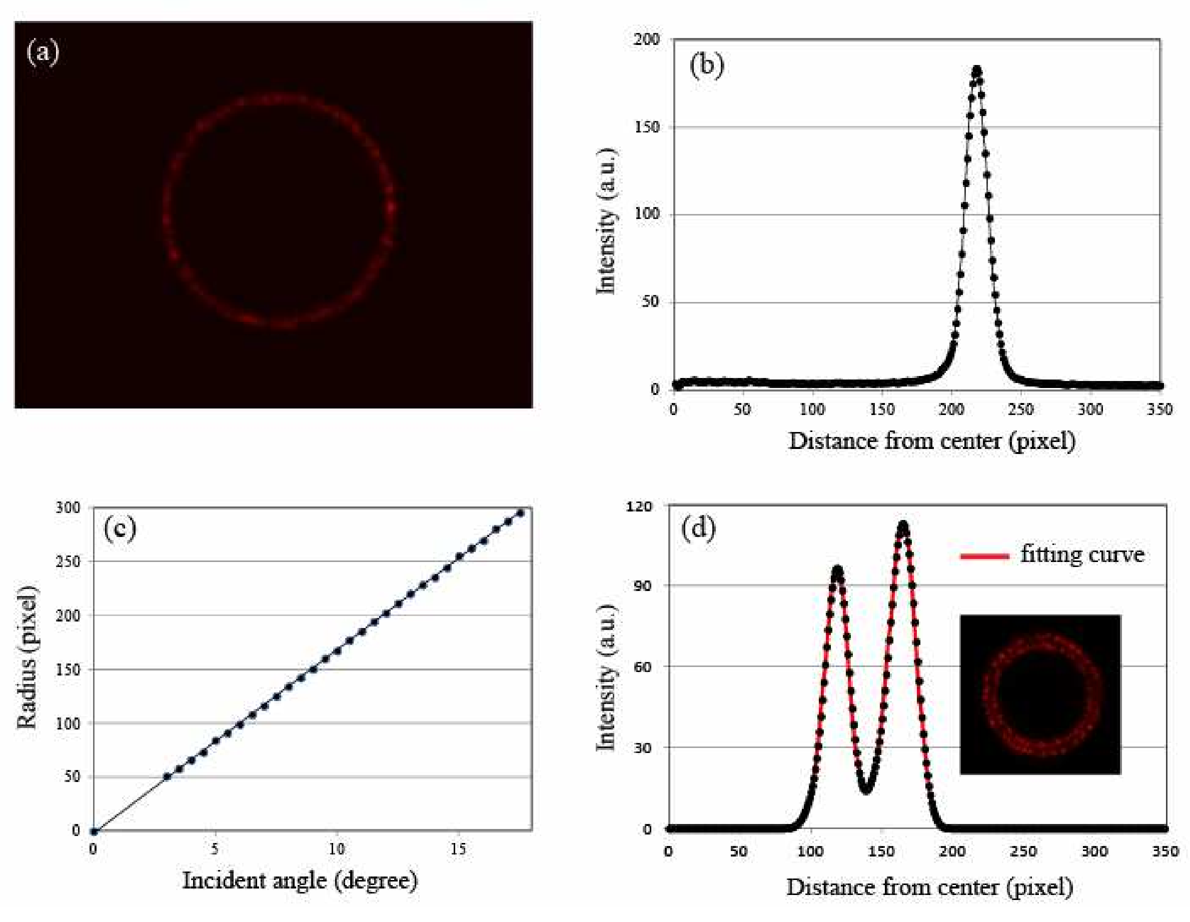


Fig. 5 Observation of photon movement using an MMF. (a) Image of a circle at the exit surface of the fiber when light entered the fiber obliquely, (b) the intensity distribution with respect to the distance from the center of the circle, (c) the correlation between the incident angle and the radius of the circle, and (d) the intensity distribution when light waves entered from two directions.

Figure 6(c) shows a vector diagram of photon motion. The length of the vector was normalized by the maximum value of each row ($x$-axis direction). Since the optical fiber diameter was 50 μm, interference fringes could not be observed near the slit. However, even in that case, if the photons including multiple momentums incident on the optical fiber, multiple vectors were observed. The photons in the vicinity of the slit proceeded straight to the center of the slit and spread in the left and right directions at both ends of the slit. Photons were emitted from each point of the slit in a particular direction, rather than in all directions. Photons emitted from both slits propagated and intersected at a position where z was several millimeters (i.e., two vectors were measured). Further away from the slit, photons on the bright band of the interference fringes moved along the bright band, while photons on the dark band traveled intersecting. The length of the vector on the dark band was longer near the double-slit but gradually decreased and remarkably shortened near $z$ = 15 mm. Thus, the photons on the dark bands were gradually absorbed by the bright bands, and the number of the photons decreased. The crossing of photons was consistent with the results of a previous study [13].

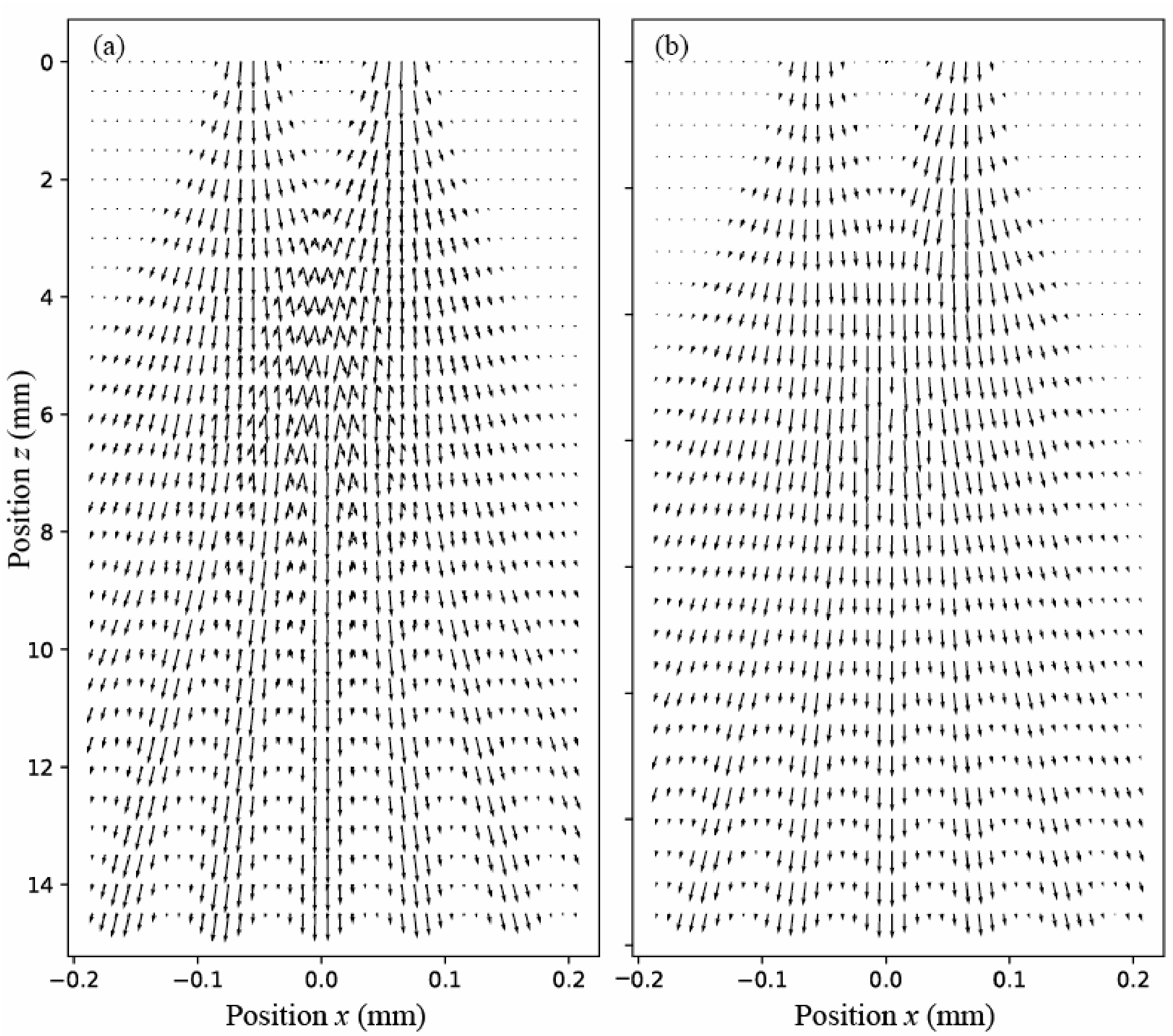


Fig. 6 Vector diagram showing the photon movement near the double-slit (a) and the averaged diagram (b).

Even when the light emitted from the fiber formed two circles, as shown in Fig. 4(d), interference fringes were observed in Fig. 6(a). Thus, the interference effect was observed, although the light waves hardly overlapped on the CCD surface. This result can be similarly explained by the interpretation explained in the SMF experiment.

The de Broglie–Bohm theory does not allow vector intersections (trajectory intersections), as shown in Fig. 6(a) [7]. In Bohmian trajectories, photons emitted from each slit change their direction at the center of fringes and travel parallel to the optical axis of the laser, forming interference fringes in each area. However, photons emitted from the left and right slits penetrated the opposite region while intersecting in our experimental results, contributing to the formation of the entire fringe. Thus, Bohmian trajectories did not match the experimental results. By averaging the vectors at each point in Fig. 6(a), the vector diagram in Fig. 6(b) was obtained, and the vectors resembled Bohmian trajectories. Bohmian trajectories are considered trajectories that show the average of the original photon movement. Similarly, the trajectories obtained in Ref. [8] are also considered to be the averaged photon motion.

## 4. Conclusion

To examine quantum mechanics, we conducted experiments on simultaneous measurements of particles and waves that violate the Englert–Greenberger duality relation, experiments in which the wave packet does not collapse, and interpretation of nonlocal interactions by electromagnetics. In this experiment, we showed again that particle and wave properties are independent using the transmission properties of the optical fiber and that the photon trajectories in the double-slit differ from Bohmian trajectories. Since these experimental results contrast the principles of quantum mechanics, further investigation with experiments and theory seems necessary.

Normal laser light was used as the light source in these experiments. In the future, experiments with single photons will be conducted to examine the change in photon momentum in more detail.

## REFERENCES


[1] W. Rueckner, "A lecture demonstration of single photon interference", Am. J. Phys. **64**, 184(1996).

[2] R. Shankar, *Principles of Quantum Mechanics* , Springer (1994).

[3] F. Giacosa, "On Unitary Evolution and Collapse in Quantum Mechanics", Quanta. **3**,

156(2014).

[4] D. Bohm, "A Suggested Interpretation of the Quantum Theory in Terms "Hidden" Variables. I", Phys. Rev. **85**, 166(1952).

[5] D. Bohm, "A Suggested Interpretation of the Quantum Theory in Terms of "Hidden" Variables. II", Phys. Rev. **85**, 180(1952).

[6] C.R. Leavens, "Timing quantum particles from the perspective of Bohmian mechanics" Superlattices Microstruct. **23**, 795(1998).

[7] D. Bohm, B. J. Hiley and P. N. Kaloyerou, "An ontological basis for the Quantum theory", Phys. Reports **144**, 321 (1987).

[8] S. Kocsis, B. Braverman, S. Ravets, M. J. Stevens, R. P. Mirin, L. K. Shalm, A. M. Steinberg, "Observing the Average Trajectories of Single Photons in a Two-Slit Interferometer", Science **332**, 1170(2011).

[9] K. Sakai, "Simultaneous measurement of wave and particle properties using modified Young's double-slit experiment", Journal for Foundations and Applications of Physics **5**, 49 (2018).

[10] K. Sakai, "Experimental verification of wave packet collapse using fourth-order interference", Journal for Foundations and Applications of Physics **5**, 216 (2018).

[11] K. Sakai, "Comment on Aspect's experiment: classical interpretation", Journal for Foundations and Applications of Physics **6**, 11 (2019).

[12] K. Sakai, ""Spooky" interaction and non-classical interference interpreted by a product of classical electric field", Journal for Foundations and Applications of Physics **6**, 103 (2019).

[13] K. Sakai, "Photon trajectories contrary to the de Broglie-Bohm interpretation", Journal for Foundations and Applications of Physics **6**, 146 (2019).