Experimental Verification on the Foundation of Quantum Mechanics
- Uncover the photon path and non-collapsing wave packet -

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Quantum mechanics has been strictly and extremely accurately verified in a wide range of fields, but several controversies remain on the interpretation of quantum mechanics. These views differ fundamentally in terms such as "Is quantum mechanics deterministic or probabilistic?", "Does a wave packet collapse?" and "Wave function really exists?". We report on our experiment, which appears to affect the interpretation of quantum theory. First, we introduce experiments on the photon path determination using the modified Young's double slit. Then, we show that a wave packet does not collapse using the modified fourth-order interference experiment. We also review a state of entangled light, show that the probabilities of simultaneous measurement of classical theory and quantum mechanics coincide, and question the necessity of the non-local interaction.

Keyword: *Interpretation of quantum theory, Duality, Wave packet collapse, Entangle state, Non-local interaction*

1. Introduction

Since Einstein and Bohr's debate, a lot of discussion has been done on the justification and interpretation of quantum mechanics. Despite numerous discussions and experiments for nearly a century, physicists and philosophers continue having disagreements and cannot give correct answers. Although all proposed interpretations are interesting, claims are different in points such as "deterministic", "wave-function reality", "hidden variables", "collapsing wave-function", "local dynamics", and "universal wave-function". There are no decisive factors as to which interpretation is right. Quantum mechanics has several basic principles that support theory. We revalidate its principle and study whether the correct theory can be experimentally decided. This paper introduces some of our verification experiments including theoretical considerations. In section 2, we describe the experiment to determine the slit of Yang's double slit through which a photon passes. In section 3, we describe the experiment to verify the collapse of the wave packet using the fourth-order interference. Finally, we discuss the expression of the entangled light and simultaneous measurement in section 4.

2. Determination of the photon path in Young's double slit

The experiment of Young's double slit is famous as Einstein and Bohr's dedicated discussion at the 5th Solvay conference, and it is a fundamental principle of quantum mechanics relating to "reality"[1]. We have developed an apparatus as shown in Fig. 1 (see reference[2] for details). A weak light emitted from a light source passes through the double slits (horizontal and vertical polarizing plates are attached to each slit), enters a Wollaston prism, and is reflected in two directions. After passing through a cylindrical lens and a polarizing plate (45 degrees), these lights overlap at the position of an optical fiber surface. On the fiber surface, interference fringes appear in the x-axis direction as shown in Fig. 1. Since the fiber is disposed at an angle of approximately 6 degrees with respect to the z-axis, the light incident from directions A and B has different incident angles. The light emitted from the output end of the fiber is imaged by an image intensifier and a CCD. As shown in Fig. 2, the light incident from direction A is arranged on the inner concentric circle, and the light in direction B draws the outer circle. The fiber diameter is 50 μm. The measurement of the photon position and number of photons while moving the fiber in the x-direction gives interference fringes as shown in Fig. 3.

In the region from the double slit to the polarizer (45 degrees), the photon path is determined by the polarization direction. That information is destroyed by the polarizer, but the information of "which way" is retained by the momentum in the y-direction. Accordingly, the path of A or B is distinguished from the position (radius) of

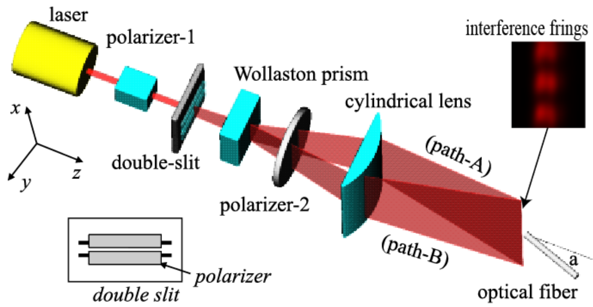

Fig. 1. Modified double-slit interferometer. The polarizing plates in the x- and y-directions are attached to each slit of the double slit. The optical fiber is on the yz-plane and inclined at approximately 6° (denoted by "a") from the z-axis.

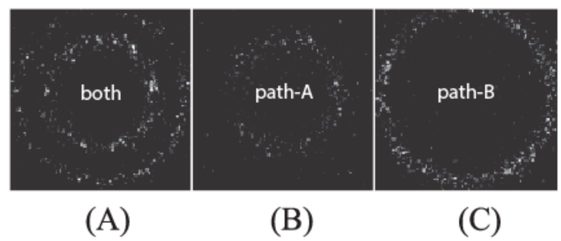

Fig. 2. (A) CCD image of the light wave emitted from the fiber when path A and path B are opened; (B) and (C) images when only either path A or path B is opened.

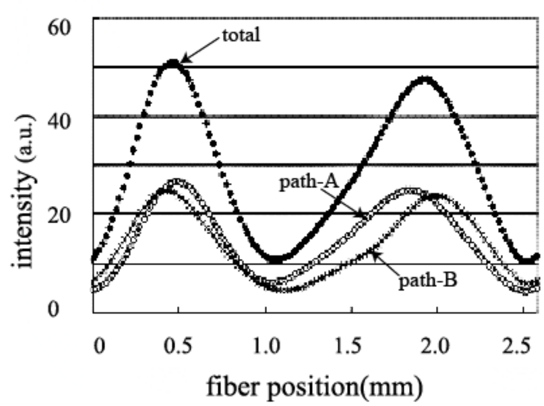

Fig. 3. Intensity distribution of the interference fringe obtained from the CCD image.

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[1] P. A. M. Dirac. The Principles of Quantum Mechanics. (Oxford: Clarendon Press,1958). J. A. Wheeler and W. H. Zurek. Quantum Theory and Measurement. (Princeton University Press, 1983).

[2] K. Sakai, "Simultaneous measurement of wave and particle properties using modified Young's double-slit experiment", Journal for Foundations and Applications of Physics 5, (2018): 49-54.

the photon on the CCD, and the polarization direction when entering the double slit is determined. As a result, the slit through which the photon has passed is decided. In our experiment, the inequality of Englert-Greenberger duality relation[3] does not hold (the value is approximately 1.3). The main point of this experiment is that we observe the wave property in the x-axis direction and the particle property in the y direction. Therefore, the results in only the x-direction and only the y-direction satisfy the expression of Englert-Greenberger duality relation. In this manner, the slit through which the photon passed is determined while observing the interference.

3. Collapse of wave packet.

The wave packet collapse[4] is an important axiom of the Copenhagen interpretation. We performed an experiment to verify the wave packet collapse by applying the fourth-order interference effect using two independent light sources. Mandel et al. theoretically and experimentally proved interference fringes with 100% visibility in the fourth-order interference[5]. In the optical system of Mandel et al., the detector position of each photon is on the same plane, but the fourth-order interference can be

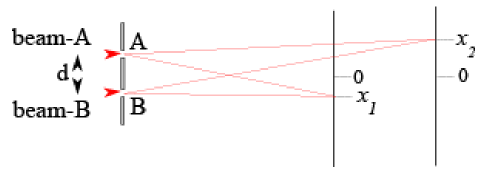

Fig. 4 Optical system to observe the fourth-order interference obtained in two spatially separated regions

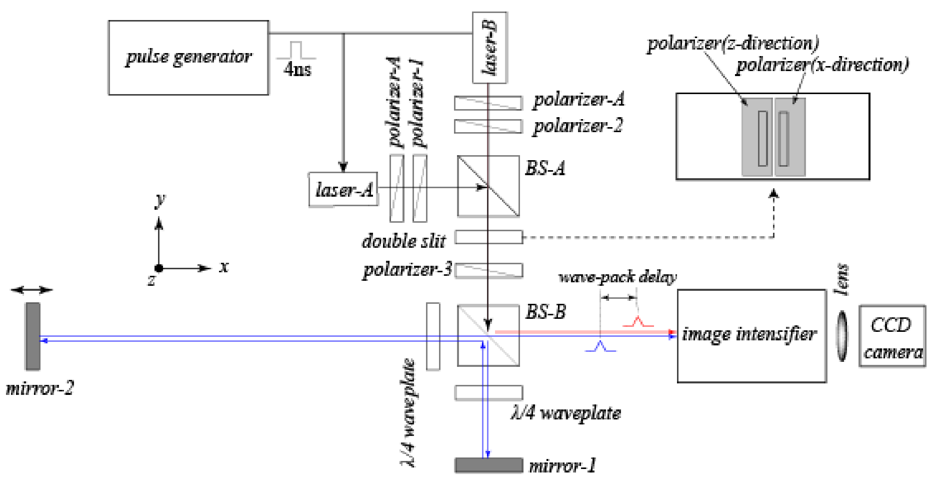

Fig. 5 Apparatus to observe the fourth-order interference using short (red) and long (blue) optical paths. A wave packet of approximately 4 ns is emitted from the independent lasers. The polarizing plate is arranged so that each light wave passes through only one of the double slits. The wave packets are divided by the polarizing beam splitter BS-B into a short optical path and a long optical path, and they enter the image intensifier.

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3 B.-G. Englert, "Fringe Visibility and Which-way Information: An Inequality", Phys. Rev. Lett. 77 (1996): 2154-2157.

4 A. Bassi, K. Lochan, S. Satin, T. P. Singh, and H. Ulbricht, "Models of wave-function collapse, underlying theories, and experimental tests", Rev. Mod. Phys. 85 (2013): 471-527.

5 R. Ghosh and L. Mandel, "Observation of nonclassical effects in the interference of two photons", Phys. Rev. Lett. 59 (1987): 1903-1905. L. Mandel, "Photon interference and correlation effects produced by independent quantum sources", Phys. Rev. A 28 (1983): 929 -943. R. Ghosh, C. K. Hong, Z. Y. Ou, and L. Mandel, "Interference of two photons in parametric down conversion", Phys. Rev. A 34 (1986): 3962-3968.

obtained even if the distance from the slit to the detection surface is different as shown in Fig. 4[6]. If the distance between the detection surfaces is sufficiently longer than the wave packet, it is expected that if the photon is detected in a short optical path, and the wave packet in a long path should collapse.

The experimental setup is shown in Fig. 5. Wave packets of approximately 4 ns from independent light sources pass through horizontal and vertical polarizing plates and are incident on the double slit. Since vertical and horizontal polarizing plates are also attached to respective slits of the double slit, wave packets of the independent light sources pass through each slit and simultaneously proceed. After passing through the 45-degree polarizing plate, the wave packet pairs are divided into a long optical path and a short optical path by a polarization beam splitter and wave plates, amplified by an image intensifier, and imaged on the CCD. A slope was added to the long optical path by a mirror, so that wave packets of the long and short optical paths did not overlap. The intensity was adjusted so that each wave packet included at most one photon / pulse on average. The difference in optical path length was adjusted at the position of the mirror, and two experiments were performed: case A: the difference is shorter than the length of the wave packet; case B: the difference is longer than the length of the wave packet. In case A, the fourth-order interference similar to the experiment by Mandel et al. was obtained because of the overlapping wave packet (Fig. 6 (b)).

Case B requires attention in analysis because the wave packet collapse is involved. Since the optical path difference is longer than the length of the wave packet, if a photon is detected in the short optical path (the light source that emits the photon is not known), one of the wave packets of the long optical path must collapse. In other words, in case B, the fourth-order interference should not occur. However, as shown in Fig. 6 (c), almost the same fringe as case A was observed. The wave packet collapse did not occur!

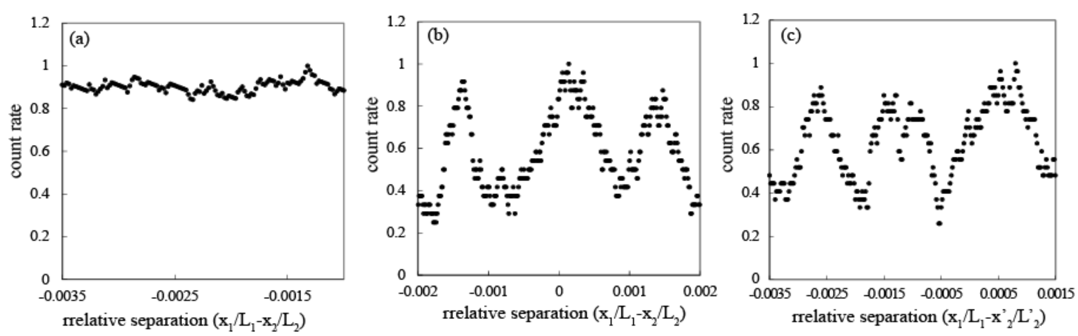

Fig. 6 Count rate against the relative separation (normalized so that the maximum value is 1): (a) for the short-short path using only laser A, no interference is observed; (b) for the short-short path using both laser A and laser B, the ordinal fourth-order interference is observed; (c) for the short-long path using both laser A and laser B, a clear interference is observed, although one of the wave packets in the long path should be collapsed.

6 K. Sakai, "Experimental verification of wave packet collapse using fourth-order interference", Journal for Foundations and Applications of Physics 5 (2018): 216-224.

4. Non-local correlation

In the experiment described in the previous section, no collapse of the wave packet was observed, but the question arises as to whether this result is consistent with the results of Aspect's experiments[7], Franson's experiments[8], etc. The "Bell-test" experiments have suggested a "spooky" interaction beyond the speed of light. Many of them are experiments of simultaneous measurement using the entangled light obtained by the spontaneous parametric down conversion (SPDC) as a light source. Franson has stated that the visibility of interference fringes is 100% in quantum theory and 50% in classical theory in his proposed experiment; consequently, classical theory cannot break Bell's inequality. This section shows that by treating the electric field of the entangled light as follows, identical probabilities or visibilities of the simultaneous measurement can be obtained in both classical theory and quantum theory.

In the simultaneous measurement, the signal and idler photons are divided into their optical paths; after they pass through the polarizing plates or interferometers on the optical paths, we independently perform simultaneous measurements at two points separated from each other by a sufficient distance. As a result, some correlation is obtained, and since its probability is different from classical theory, it claims the existence of quantum mechanical effects and non-local interaction. When the positive frequency parts of the field of the signal and idler photons are represented by $\hat{E}_s^{(+)}(\boldsymbol{r}_s)$ and $\hat{E}_i^{(+)}(\boldsymbol{r}_i)$, the probability $P_q(\boldsymbol{r}_s,\boldsymbol{r}_i)$ of simultaneous measurement in quantum mechanics is

$$P_q(\boldsymbol{r}_s,\boldsymbol{r}_i) = \langle 1_s,1_i | \hat{E}_s^{(-)}(\boldsymbol{r}_s)\hat{E}_i^{(-)}(\boldsymbol{r}_i)\hat{E}_i^{(+)}(\boldsymbol{r}_i)\hat{E}_s^{(+)}(\boldsymbol{r}_s) | 1_s,1_i \rangle \tag{1}$$

By replacing the operator with the classical number, we obtain the probability $P_c(\boldsymbol{r}_s,\boldsymbol{r}_i)$ of simultaneous measurement of classical theory

$$P_c(\boldsymbol{r}_s,\boldsymbol{r}_i) = \langle E_s^{(-)}(\boldsymbol{r}_s)E_i^{(-)}(\boldsymbol{r}_i)E_i^{(+)}(\boldsymbol{r}_i)E_s^{(+)}(\boldsymbol{r}_s) \rangle \tag{2}$$

Since the state vector gives restrictions in the calculation process, quantum mechanics and classical theory have different results. Here, we consider the entangled state. In Aspect's experiment, for example, the entangled state is represented by the product of states (tensor product) such as $|H\rangle_s|H\rangle_i + |V\rangle_s|V\rangle_i$, where H and V are the polarization states in the horizontal and vertical directions, respectively. By transforming the electric field $E^{(+)}(\boldsymbol{r},t)$ of the pump light, the shape of this product is expressed as

$$\begin{aligned} E^{(+)}(\boldsymbol{r},t) &= A_0 e^{i(\boldsymbol{k}\cdot\boldsymbol{r}+\omega t)} \\ &= A_s e^{i(\boldsymbol{k}_s\cdot\boldsymbol{r}+\omega_1 t)} A_i e^{i(\boldsymbol{k}_i\cdot\boldsymbol{r}+\omega_2 t)} \end{aligned} \tag{3}$$

[7] A. Aspect, P. Grangier, G. Roger, "Experimental Tests of Realistic Local Theories via Bell's Theorem", Phys. Rev. Lett. 47 (1981): 460-463. A. Aspect, J. Dalibard, G. Roger, "Experimental Test of Bell's Inequalities Using Time-Varying Analyzers", Phys. Rev. Lett. 49 (1982): 1804-1807.

[8] J. D. Franson, "Bell inequality for position and time", Phys. Rev. Lett. 62 (1989): 2205-2208.

Here, A_s and A_i are the amplitudes of the signal and idler lights, $\boldsymbol{k}_s$ and $\boldsymbol{k}_i$ are the wave numbers of the respective lights, and ω_s and ω_i are the angular frequencies. The equation in the first row corresponds to the electric field of the pump light, and the second row corresponds to that in the entangled state. The equation clearly shows that momentum and energy are conserved. When the entangled state is expressed by Eq. (3), the probability of simultaneous measurement is identical to that obtained by measuring the pump light and represented by the second-order interference. Thus, the period of interference fringes depends on the wavelength of the pump light in the experiment of simultaneous measurement. With this form, the probability of simultaneous measurement is identical for both quantum mechanics and classical theory. As an example, the analysis of Aspect's experiment is shown. The light emitted from the light source is detected after passing through polarizing plates of θ_1 and θ_2, respectively. A positive frequency part of the field corresponding to $|H\rangle_s |H\rangle_i + |V\rangle_s |V\rangle_i$ is given by

$$E^{(+)}(r_A, r_B) = (a_{s1}\cos\theta_1 e^{ik_s \cdot r_A}) \cdot (a_{i1}\cos\theta_2 e^{ik_i \cdot r_B}) + (a_{s2}\sin\theta_1 e^{ik_s \cdot r_A}) \cdot (a_{i2}\sin\theta_2 e^{ik_i \cdot r_B}) \quad (4)$$

a_{s1}, a_{i1}, a_{s2} and a_{i2} are amplitudes of the electric field (directions of detectors are represented by A and B). Assuming that $a_{s1} = a_{i1} = a_{s2} = a_{i2} = 1$, probability P_{c2} ($\boldsymbol{r}_A$, $\boldsymbol{r}_B$) of the simultaneous measurement by classical theory is

$$P_{c2}(\boldsymbol{r}_A, \boldsymbol{r}_B) = \frac{1}{2}\cos^2(\theta_1 - \theta_2)\,. \quad (5)$$

This result is consistent with the result of quantum mechanics and violates Bell's inequality. Mandel et al.[9], Franson[10] and Ou et al.[11] reported various types of experiments using entangled light. The analysis of these experiments also has the same result in quantum mechanics and classical theory if we use the description of the above electric field.

With these results alone, we cannot determine the validity of each interpretation, but we cannot recommend the interpretation of "denying reality" or the interpretation based on the "wave packet collapse or non-local interaction". We believe that the observation of the wave function is necessary for further elucidation of quantum mechanics. It is our future aim to challenge the detection of "ghost" waves.

I hope that an international experimental project for the interpretation of quantum mechanics will be established.

[9] R. Ghosh and L. Mandel, "Observation of nonclassical effects in the interference of two photons", Phys. Rev. Lett. 59 (1987): 1903-1905.

[10] J. D. Franson, "Bell inequality for position and time", Phys. Rev. Lett. 62 (1989): 2205-2208.

[11] Z. Y. Ou, X. Y. Zou, L. J. Wang and L. Mandel, "Observation of nonlocal interference in separated photon channels", Phys. Rev. Lett. 65 (1990): 321-324. Z. Y. Ou, X. Y. Zou, L. J. Wang and L. Mandel, “Experiment on nonclassical forth-order interference”, Phys. Rev. A 42 (1990): 2957-2965.

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