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Photon trajectories contrary to the de Broglie-Bohm interpretation

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Abstract

The de Broglie-Bohm interpretation was built to perform the same statistical predictions as a standard quantum theory in every conceivable physical situation, and the two theories cannot be distinguished. In this study, the trajectories of crossed photon pairs were examined, and different results were obtained under certain conditions even when there were no differences in the statistical measurements. The conditions and experimental results showed that the trajectories of photons followed the standard interpretation of quantum theory with high probability.

Keywords: de Broglie-Bohm interpretation, standard quantum theory, photon trajectory, crossed beam

1. Introduction

The Copenhagen interpretation of quantum mechanics is superior at correctly predicting experimental results and is suitable for all practical purposes. However, understanding quantum mechanics using the Copenhagen interpretation is difficult [1]. An attempt to add trajectories to quantum mechanics was made by Bohm [2,3] in 1952. In his interpretation, the wave field forms a quantum potential, and the particles move according to a Hamilton–Jacobi-like equation. The de Broglie-Bohm interpretation is different from the non-deterministic and non-realistic Copenhagen interpretation, but the predicted results of the de Broglie-Bohm interpretation are equivalent to other quantum mechanical interpretations. However, in 1992, Englert, Scully, Sussmann, and Walther [4] called the Bohmian trajectory "surrealistic."

Recently, Kocsis et al. published the results of observing photon trajectories in double-slit interference experiments [5]. These photon trajectories were remarkably similar to the trajectories presented by Philippidis, Dewdney, and Hiley [6], which supported the de Broglie-Bohm theory. However, re-examination was performed concerning their experiment, and the trajectory shown by Kocsis et al. was shown to have an average trajectory, rather than the trajectory of individual photons [7,8]. Therefore, the debate over the legitimacy of the Bohmian trajectory continued. Its conclusions are noteworthy; it relates to the validity of the various proposed interpretations of quantum mechanics. As a note, since the Copenhagen interpretation does not contain the concept of particle trajectories, this paper refers to the Copenhagen interpretation as the standard interpretation.

The authors have conducted experimental verifications on the interpretation of quantum mechanics (such as wave-particle duality and wave packet collapse) [9-12]. Although an experimental distinction between the de Broglie-Bohm and standard interpretations is considered impossible, the photon trajectories of each interpretation have been found to differ in intersecting beams under certain conditions. In a specific condition, a trajectory according to the de Broglie-Bohm interpretation never occurs, but the trajectory according to the standard interpretation is observed with a probability of 100% and vice versa. This paper proposes a method to verify whether a photon behaves like the Bohmian trajectory (changing the direction of motion at the intersection of beams) using two photons generated by a spontaneous parametric down-conversion (SPDC). This study showed that photons did not follow the Bohmian trajectory.

2. Photon trajectories in intersecting beams

In classical physics, particles move in the potential V according to Newton's laws, while in the de Broglie-Bohm interpretation, particles move in the field where the quantum potential Q is added to the classical potential V. The equation of the de Broglie-Bohm interpretation resembles the Hamilton-Jacobi equation except for an additional term, Q. One important feature to notice about Bohmian trajectories is that the trajectories do not cross. This is a consequence of the single-valued nature of the field equation [13].

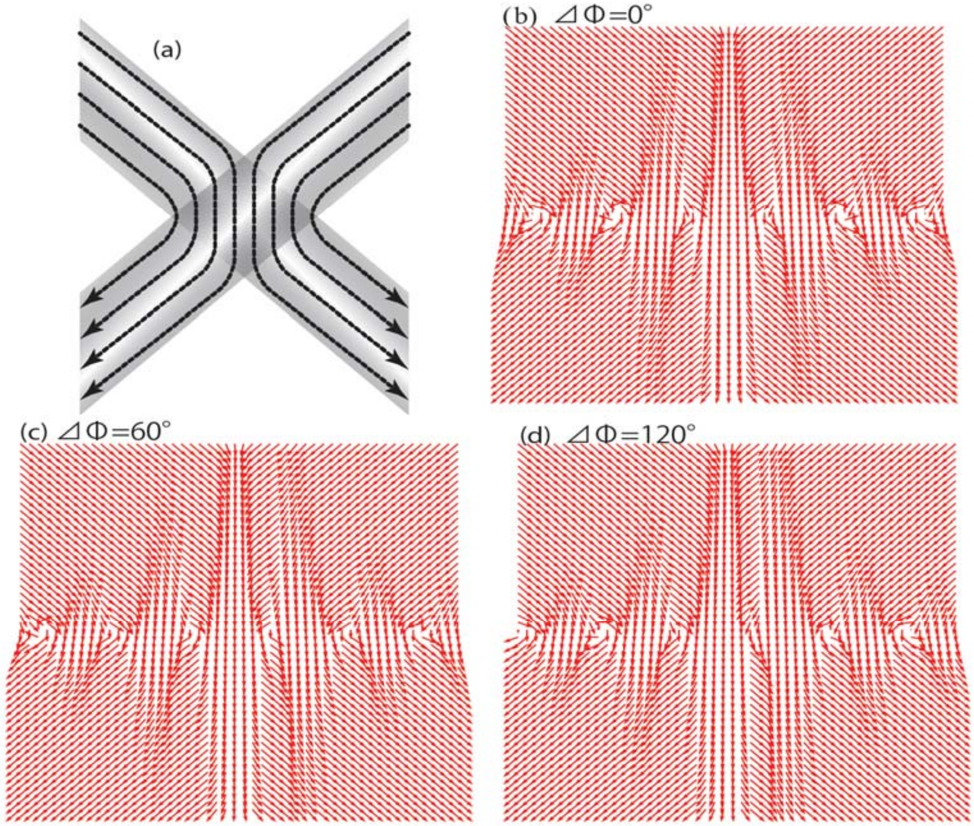

Fig. 1. (a) Schematic view of the Bohmian trajectories of photons in the crossed beams incident from the ± 45° direction. (b, c, d) Vector diagrams (ignoring magnitude) of Bohmian orbit obtained by simulation near the center of the crossed beams. The phase difference between left and right beams was 0, 60, and 120 degrees, respectively.

Figure 1 (a) shows an overview of Bohmian trajectories when two beams intersect. The photon movement gradually changes its path so as to move onto the other photon's wave function in the crossing region. Figure 1 (b) is an enlarged view of the vicinity of the intersection of the Gaussian beams (simulation). Arrows indicate the direction of movement of photons (ignoring magnitude). Interference fringes are seen near the center, and photons move in a complex manner. Figures 1 (c) and 1 (d) show the movement of photons when the phase difference between the two beams was 60 and 120 degrees. Although Figs. 1 (c) and 1 (d) are slightly displaced to the left compared to Fig. 1(b), the overall flow of photons remained unchanged; the overall flow of photons was independent of the phase difference of the two beams. On the other hand, since the probability of detection of photons in the lower left and lower right was proportional to the square of the wave function, the detection probability of the photon remained the same for the Bohmian trajectory as for the standard interpretation. Therefore, whether photons passed or did not pass the Bohmian orbit could not be determined.

The trajectories of two photons emitted from SPDC were considered to distinguish the Bohmian trajectory and the trajectory of the standard interpretation. As shown in Fig. 2, two photons entered from the top simultaneously and were split into two light paths. The beams at both ends entered detector A or D, and the central beams entered detector B or C after crossing. First, when one photon was detected by detector A, a photon incident from the right optical path passed through the central optical path. In the Bohmian trajectory, the photon should change its path at the intersection of beams and enter detector C (Fig. 2 (b)). On the other hand, according to the standard interpretation, it should enter detector B (Fig. 2 (a)). Therefore, if the photon passes on the Bohmian trajectory, the probability of simultaneous detection of detectors A and B must be zero (in other words, the detection probability of A and C is 100%). Conversely, in the standard interpretation, the probability of simultaneous measurement by detectors A and C should be zero (100% detection probability of A and B). Thus, when a photon was detected by detector A, it was possible to distinguish between the de Broglie-Bohm interpretation and standard interpretation depending on whether the other photon was detected by detector B or by detector C. The case where one photon was detected by detector D could be considered similarly.

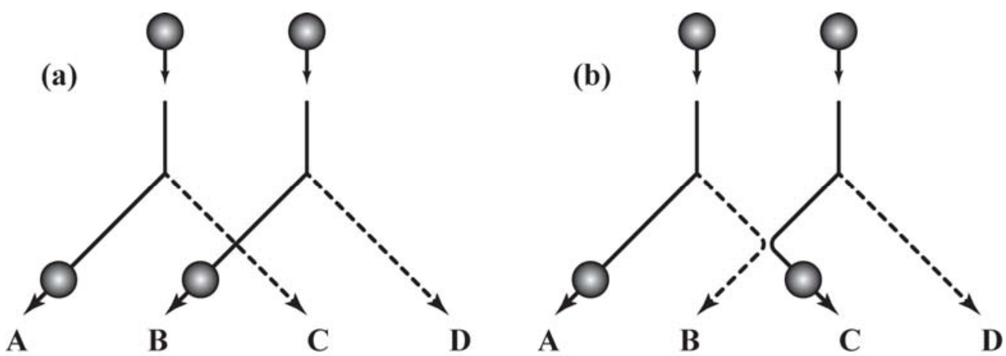

Fig. 2. Diagram of the photon trajectories. (a) The trajectory of standard interpretation. (b) The trajectory of the de Broglie-Bohm interpretation.

When using a general light source instead of SPDC, a combination of two photons in the left beam and zero photons in the right beam was also included (or vice versa) in addition to the combination of photons shown in Fig. 2. Therefore, it was not possible to distinguish between the trajectory of the standard interpretation or the trajectory of the de Broglie-Bohm interpretation using a general light source.

3. Experiment and results

The outline of the apparatus used for the experiment is shown in Fig. 3. Pulsed light (pulse width = 1 ms) from a semiconductor laser (405 nm; 200 mW) was focused by a lens and passed through a 405 ± 10 nm band-pass filter, a polarizing plate P1 for light intensity adjustment, and a 45° polarizing plate P2. Then, the light was incident on Type-II BBO crystal (θ = 42.6°; Φ = 30 °).

The signal light (horizontal polarization direction) and the idler light (vertical polarization direction) from the BBO crystal traveled separately in the respective directions. Using a Wollaston prism W1, the relative angle between the two light paths was increased, and the light was then focused by another lens. The outline of the light path of the signal and idler lights is illustrated in Fig. 3 with red and blue lines, respectively. After passing through the 810 ± 10-nm band-pass filter, the two light waves passed through the polarizing plate P3 (45° direction) and were separated again into light paths of horizontally and vertically polarized lights by the Wollaston prism W2. Then, the position of the Wollaston prism was adjusted so that the central rays intersected. The polarizing plate P4 (45° direction) was used to align the polarization directions of the four light waves. The light focused by the lens was detected by an image intensifier (HAMAMATSU C2700 multi-alkali photocathode type).

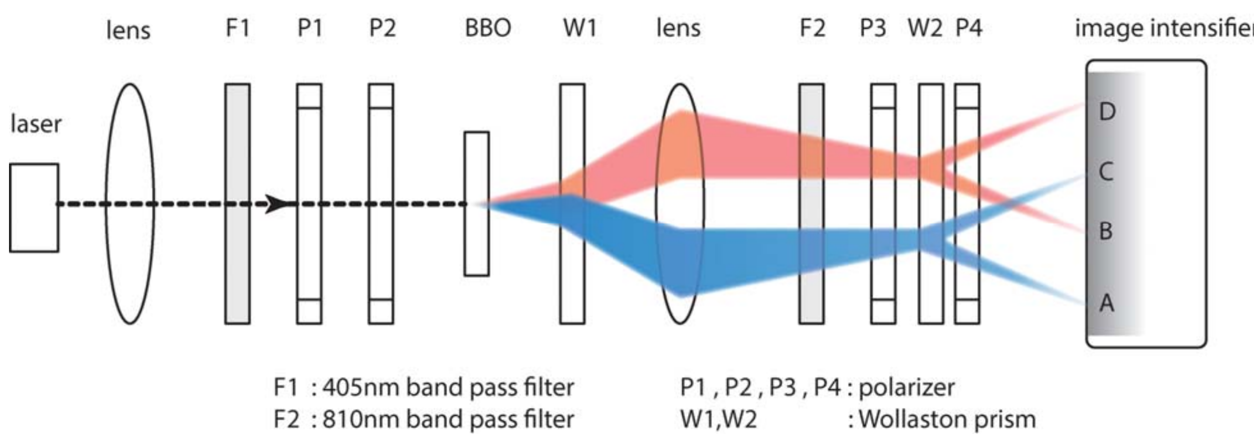

Fig. 3. Experimental equipment to verify the Bohmian trajectory. Laser (405 nm) light passed through filter F1 and polarizing plate P1 and entered the Type-II BBO crystal. Photon pairs passed through the lens after their relative angles were expanded with the Wollaston prism W1. The light was again separated into two light waves by the Wollaston prism W2 and imaged onto the image intensifier. The paths of signal and idler lights were shown by red and blue lines, respectively.

Figure 4 shows an image obtained by the image intensifier. A, B, C, and D correspond to the detectors A, B, C, and D of Figs. 2 and 3. The light intensity was adjusted using the polarizing plate P1 to observe several photons. In the experiment, measurement was performed only when two photons were detected (measurements of A-B, A-C, B-D, or C-D, except A-A, B-B, C-C, D-D, A-D, and B-C). An example of an observed photon pair image is also shown in Fig. 4. The photon pairs were counted using 25000 pulses per experiment, and each experiment was performed four times (10^5 pulses in total).

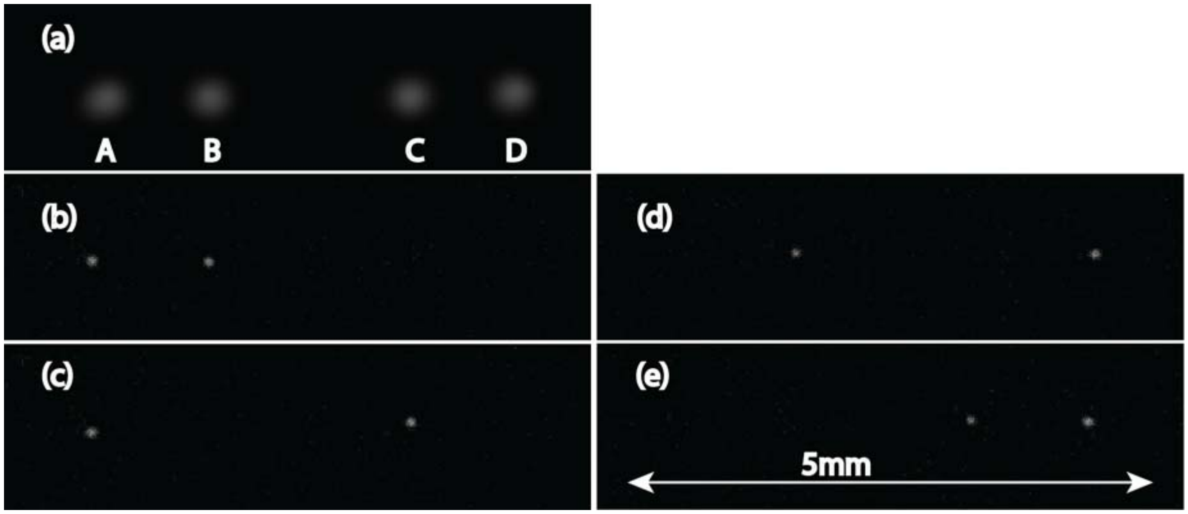

Fig. 4. Photon distribution on the image intensifier. (a) Image with many photons (Gaussian filter applied). (b-e) Image examples when one photon pair was observed.

Ideally, one photon pair should be output by SPDC; however, a number of photon pairs according to the Poisson distribution existed in the experimental system. Therefore, cases when two or more photon pairs were generated had to be considered. First, when one photon pair was generated, the detection probability P_1' detected in A-B, A-C, B-D, or C-D was given by the following equation:

$$P_1' = \frac{1}{2} P_1 P_d^{\,2} \tag{1}$$

Where P_1 is the probability that one photon pair is generated by one laser pulse, and P_d is the detection efficiency of the experimental system (detection efficiency of the image intensifier, a transmittance of the polarizing plate, etc.). Since the combination of A-A, B-B, C-C, D-D, A-D, and B-C was excluded from the measurement, a factor of 1/2 appeared.

The combination of two photons is represented by a dotted line in Fig. 5. Photon pairs shown in Fig. 5 (a) were effective for the experiment (effective for verifying the Bohmian trajectory). However, the combinations of photons shown in Figs. 5 (b) and 5 (c) were invalid photon pairs for the results of this experiment because the generation time was different and wave packets did not pass through the intersection at the same time. Photon pairs were detected only in A-C or B-D in the case of Fig. 5 (b) and only in A-B or C-D in the case of Fig. 5 (c), except for the pairs A-A, B-B, C-C, D-D, A-D, and B-C. The sum of the detection probability P_2' of those probabilities was given by the following equation:

$$P_2' = P_2 P_d^{\,2}(1 - P_d)^2 + P_2 P_d^{\,2}(1 - P_d)^2 + P_2 P_d^{\,2}(1 - P_d)^2 \tag{2}$$

Where P_2 is the probability that two pairs of photons are generated per pulse, and each term is a probability corresponding to Figs. 5(a), 5(b), and 5(c) (in this case, all had the same probability).

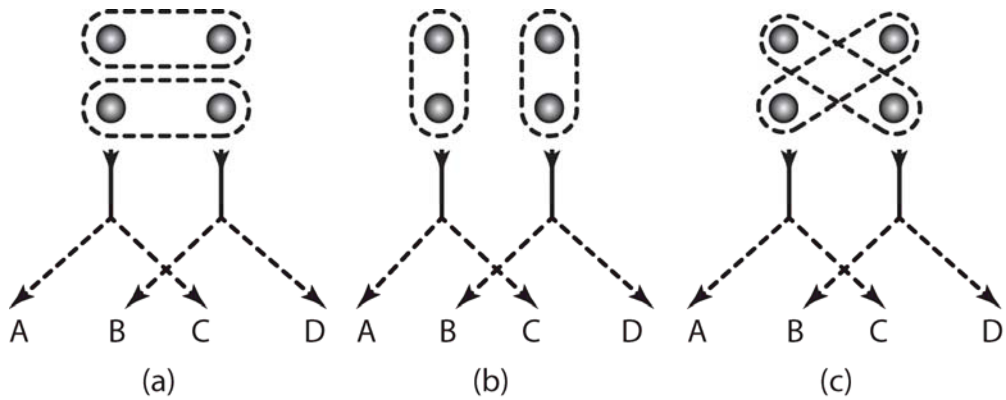

Fig. 5. Combination of photons when two pairs of photons were generated. (a) A combination effective for judging the validity of the Bohmian trajectory. (b, c) A combination ineffective for experimental results.

Similarly, the detection probability when n-photon pairs generated was as follows:

$$P_n' = \frac{n}{2} P_n P_d^{\,2} (1-P_d)^{2n-2} + \frac{n(n-1)}{2} P_n P_d^{\,2} (1-P_d)^{2n-2} + \frac{n(n-1)}{2} P_n P_d^{\,2} (1-P_d)^{2n-2} \quad (3)$$

Where P_n is a generation probability of n-photon pairs per pulse. n and $n(n$-1) are the number of photon combinations corresponding to Figs. 5(a), (b) and (c). The factor 1/2 has been described above. The first term indicates the probability that was effective for the experiment. The second and third terms indicate the probabilities of photon pairs that were detected by A-C or B-D and A-B or C-D, respectively, but were ineffective for the experiment. Therefore, the detection probability P was given by the following equation:

$$P = \sum_n \left[\frac{n}{2} P_n P_d^{\,2} (1-P_d)^{2n-2} + \frac{n(n-1)}{2} P_n P_d^{\,2} (1-P_d)^{2n-2} + \frac{n(n-1)}{2} P_n P_d^{\,2} (1-P_d)^{2n-2} \right] \quad (4)$$

The probability P'_{noise} containing noise was as follows:

$$P'_{noise} = \sum_n \left[4nP_n P_d (1-P_d)^{2n-1} P_{noise} \right] + \frac{1}{2} P_{noise}^{\,2} \quad (5)$$

Here, P_{noise} is the probability of detecting one noise (photon) in any of the areas (A, B, C, or D) when the laser was not incident. P_{noise} was about 10^{-4} in 10^5 measurements. Since this value was sufficiently smaller than P_d, the influence of noise (Eq. (5)) was ignored.

As stated above, the second and third terms in parentheses in Eq. (4) were not effective to judge whether photons passed through the Bohmian trajectory or the standard interpretation trajectory. The second term is the detection probability in A-C or B-D, and the third term is the detection probability in A-B or C-D. Therefore, these values had to be subtracted from the results obtained in the experiment (as a note, the values of the second and third terms were the same).

The number of photon pairs obtained in the experiment is shown in Fig. 6 (a). The left bar (blue) shows the number of pairs detected in A-B or C-D (corresponding to the trajectory of the standard interpretation), and the right bar (red) shows the number of pairs detected in A-C or B-D (corresponding to the Bohmian trajectory). In 10^5 pulses, 103 photon pairs (A-B, A-C, B-D, or C-D) were detected. Therefore, the detection probability P was about 0.001. Assuming that the average number of photon pairs generated per pulse was m, P_n could be calculated from the Poisson distribution, and then P was obtained using Eq. (4). The change of P with respect to m is shown in Fig. 6 (b). P_d was estimated to be 1/40 because the efficiency of the image intensifier was 1/10 and the transmittance of the two polarizing plates was 1/4. From Fig. 6 (b), m corresponding to the experimental value P = 0.001 was 1.1. Using these values, the second and third terms in Eq. (4) were calculated and subtracted from the results shown in Fig. 6 (a). The results of this calculation are shown in Fig. 6 (c). The blue bars show the number of pairs supporting the trajectory of the standard interpretation, and the red bars show the number of pairs supporting the Bohmian trajectory.

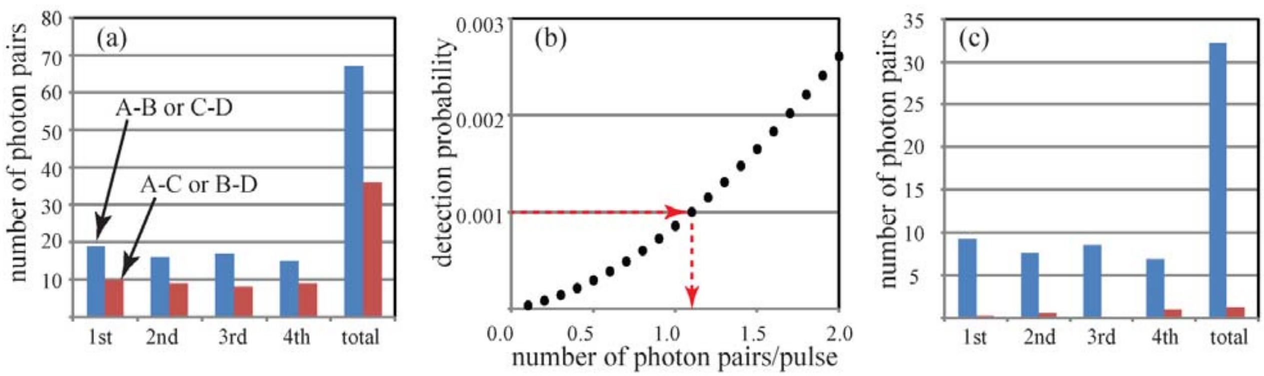

Fig. 6. (a) Number of photon pairs in the trajectory of standard interpretation (blue) and Bohmian trajectory (red). (b) Correlation between the number of photon pairs generated per pulse and the probability P calculated from Eq. (4). Since P was about 0.001 according to the experiment, m = 1.1 pairs/pulse. (c) Number of photon pairs in the trajectory of standard interpretation (blue) and Bohmian trajectory (red) corrected using Eq. (4).

The total numbers supporting the standard interpretation and the de Broglie-Bohm interpretation were 32.2 and 1.2, respectively. Thus, photons passed through the trajectories predicted by the standard interpretation with high probability (about 96%). An experiment given in a previous paper determined which slit the photon passed through in a double-slit experiment [9]. The results of this previous paper seemed to support the de Broglie-Bohm interpretation; however, this present study denied the Bohmian trajectory. Therefore, a new deterministic and realistic interpretation to understand quantum mechanics is desired.

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