Should we interpret quantum mechanics according to Bohr?

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Abstract

I present here a thought experiment which violates the most widely accepted interpretation of quantum mechanics "The Copenhagen Interpretation" and Bohr's complementarity which says that there is no meaning of the state of a particle until it is observed and the act of observation might change it. The experiment consists of a double slit apparatus which is modified by putting a second double slit apparatus between the source and the original apparatus with certain conditions imposed on both the apparatuses using the facts of interference and diffraction. A striking paradox emerges if we consider the arguments of Bohr's complementarity, i.e. the photon travels through both the paths simultaneously in a double slit apparatus whenever there is interference. It turns out that this paradox can be resolved only if the photon travels through one path even if interference fringes are visible.

Keywords: Bohr's complementarity; Copenhagen interpretation; Double slit interference; Diffraction; Path information

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1 Introduction

Quantum mechanics states that the principle of superposition is applicable if two or more paths are available for a particular event to occur with certain probability of the event evolving via a particular path. On measurement we find a particular path and this statistically gives the probability of a particular path [*5*, *6*]. Also the same principle of superposition is applicable to the waves in which multiple waves interfere with one another at some point and we get the same pattern which is unexplainable with classical particles. Hence Niels Bohr interpreted this result as it is the measuring apparatus that determines which nature of the (object) will be displayed (in our case light) [1, 2].

In the double slit apparatus the same principle of superposition is applicable to the probability of finding the photon at the detector screen which results in the interference pattern. In Dirac's notation probability of finding the particle at a particular point of the detector screen is

$$= |< s|4><4|d> + < s|5><5|d>|^2 \tag{1}$$

where $< s|4>$ signifies the probability amplitude for the photon with initial state source s and final state slit 4 [*6*].(I have intentionally numbered slits as 4 and 5 because of some reasons which will be clear as the article proceeds further)

The equations of quantum mechanics i.e. the Schrodinger equation and the uncertainty relations accurately predict the statistical outcomes of the experiments till date. But still we don't understand the physical meaning of these equations. Many people including Einstein tried to find a physical meaning of these equations but didn't succeed [*2, 5*]. The most famous interpretation among all is the Copenhagen interpretation which was led by Bohr, Heisenberg and Born. According to this interpretation there is no reality until the system is measured [*5*]. Most physicists like and believe this view of quantum mechanics. In this interpretation one of the important concepts was Bohr's complementarity [1].

According to Bohr's complementarity two measurables which are complementary to each other can't be measured simultaneously. For example momentum and position are complementary to each other. There are other complementary variables too but in the double slit apparatus, the momentum and position complementarity plays the crucial role. Since we know the wavelength i.e. the momentum [*5, 6*]

$$\lambda = \frac{h}{p} \qquad \text{(where h is the planck's constant)}$$

So we can't exactly figure out which slit the photon went through. Also even when we try to detect the slit through which the photon passed, the interference pattern washes away and the probability of finding the photon at the detector becomes the sum of the individual probabilities from both the slits i.e.

$$= \quad |< s|5><5|d>|^2 + |< s|4><4|d>|^2 \tag{2}$$

So according to Bohr's complementarity the interference pattern and which path information are complementary to each other i.e. if one happens other can't happen [*3, 4*]. It was mathematically shown by Wooters and Zurek [*5, 11*] that as the information about the slit through which the photon passed was varied, the visibility of the interference fringes is reduced, and as we get the complete path information or we completely determine the slit through which the photon passed, there is no interference. As was said by Feynmen in support of Bohr's complementarity that " *if one does say that the photon came from either of the slits and then starts to make deductions, he* *will make errors in the analysis*."[6]. So Bohr's complementarity says that when there is interference, the photon came from both the paths (In case of superposition this means that both the states are simultaneously present and the measurement causes a particular state to collapse [1, 5]).

2 Thought experiment

Let us modify our original interference apparatus such that another double slit apparatus is placed in between the source s and the slits 4 and 5 as shown in fig 1. A hole is made in the first double slit apparatus such that there is a minima at the hole 3. Till this point if we close slit 4 and 5, the apparatus is similar to the delayed choice apparatus suggested by Wheeler [*5, 7, 8*]. We know that since hole 3 is really small (not 0 but finite and the probability of finding the photon at 3 is negligible as the slit 3 width is really small compared to the fringe width) we get diffraction fringes behind 3 with maximas and minimas.

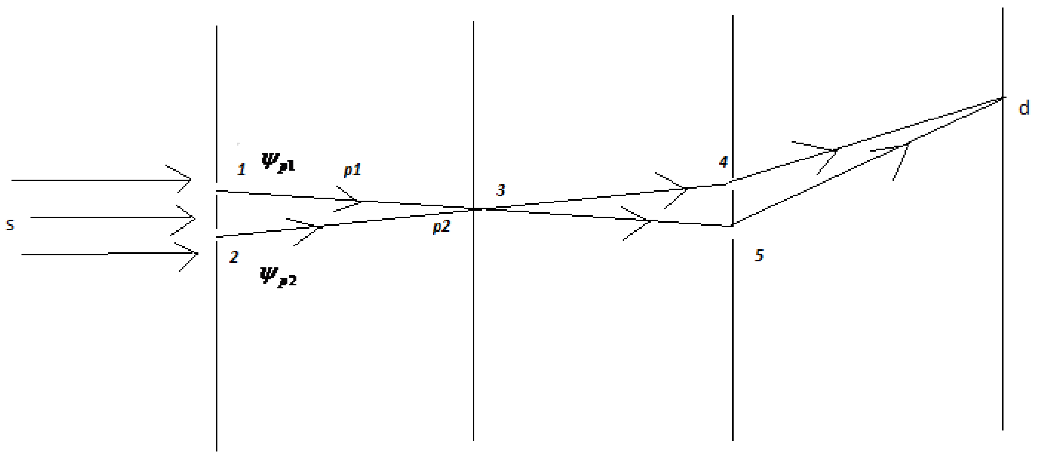

Fig 1. The modified double slit apparatus, p1 and p2 shows the possible paths for the photon to reach detector d. At hole 3 we have a minima and in the path p1the photon leaves from slit 1 goes through slit 5 and reaches d and in path p2 the photon leaves from slit 2 goes through slit 4 to reach d.

Then we place the slits 4 and 5 in such a way that slit 4 is at the minima of the beam of slit 1 but not at the minima of slit 2, and slit 5 at the minima of the beam coming from slit 2 but not at the minima of slit 1. It's like we close one of the slits either 1 or 2 and then find the corresponding minimas, and then place the slit 4 at the minima of 1 and slit 5 at the minima of 2 accordingly. This is always possible as there is a non-zero phase difference between both the beams behind 3 as both the slits 1 and 2 are at a different angle to 3. Therefore no photon which left slit 1 can reach slit 4 and no photon which left slit 2 can reach slit 5. So we make sure that the photon which reaches slit 5 comes from slit1 and then to the detector d via the path p1 and the photon which reaches slit 4 comes from slit 2 and then detector d via path p2. Therefore the probability amplitudes for the paths are

Path p1: $$\psi_{p1} = \langle s|1\rangle\langle 1|3\rangle\langle 3|5\rangle\langle 5|d\rangle \quad (3)$$

Path p2: $$\psi_{p2} = \langle s|2\rangle\langle 2|3\rangle\langle 3|4\rangle\langle 4|d\rangle \quad (4)$$

So the probability amplitude of finding the photon at the detector d is

$$= \psi_{p1} + \psi_{p2}$$

$$= \langle s|1\rangle\langle 1|3\rangle\langle 3|5\rangle\langle 5|d\rangle + \langle s|2\rangle\langle 2|3\rangle\langle 3|4\rangle\langle 4|d\rangle \quad (5)$$

Since we know that hole 3 is a minima

$$\Rightarrow \langle s|1\rangle\langle 1|3\rangle + \langle s|2\rangle\langle 2|3\rangle = 0 \quad (6)$$

$$\Rightarrow \langle s|1\rangle\langle 1|3\rangle = -\langle s|2\rangle\langle 2|3\rangle \quad (7)$$

Substituting in the equation we have the probability amplitude of finding the particle at detector d is

$$= \langle s|1\rangle\langle 1|3\rangle(\langle 3|5\rangle\langle 5|d\rangle - \langle 3|4\rangle\langle 4|d\rangle) \quad (8)$$

This shows that we have a interference pattern at the detector d with the intensity getting reduced by a factor of $|\langle s|1\rangle\langle 1|3\rangle|^2$ and the pattern gets shifted by $\lambda/2$. So this apparatus gives the interference fringes.

Now according to Bohr's hypothesis of complementarity the photon passed through both the paths p1 and p2 simultaneously since we have interference at d. But we know that in such a situation the probability of finding the photon at hole 3 is 0 because we would have interference at 3 as the photon passed through both the paths p1 and p2 simultaneously. This leads to a paradox because both the paths p1 and p2 comprises 3 and since there is some probability for finding the photon at d, the photon must pass through hole 3. But in that case the probability of finding the photon at hole 3 won't be 0. So there can't be any interference at 3. Therefore it's not possible for the photon to pass through both the paths p1 and p2 simultaneously and still get detected at the detector d. Therefore the photon passed through only one of the paths i.e. either p1 or p2 never both simultaneously even if there is interference at the detector d.

3 Results and Discussions

Question. So the photon always passes through one of the paths whenever there is interference or not. But then why isn't there interference at hole 3 when the photon passed through one path?

Answer. The reason is that if the photon passes through one of the path it doesn't mean we should always have an interference pattern (which is quite true from our daily experiences with light). Rather the interference depends on the apparatus that is put in front of the incoming beam from the source. We have interference at d because when the photon arrives at 3, the system is identical to the double slit apparatus but for the photon at slit 1 or 2 the condition is different and the system is not similar to the normal double slit apparatus but rather some modification has been made to it. We can say that there is some influence from the system which is put in front of the photon.

Question. Then why is that when the photon is detected at any of the slits, then it travels through only one of the paths but interference washes away?

Answer. As shown by Bhandari [*9*, *10*] the method of detection brings an arbitrary random phase to the beam and hence there is no interference. Also when we say that if the photon passes through only one of the slits then we add the probabilities of the paths when one slit is closed and other is open . But that's incorrect because other slit is open in the experiment and the condition is not the same. It's like the photon comes to know about the other slit and the system changes even if it went through only one slit.

4 Conclusions

Wheeler was correct in stating that the interference pattern is lost at slit 3 in the apparatus, but he was wrong in stating the reason for this observation. I have shown in this experiment that the photon always travels through one of the paths and it is the system that we put in front of the photon which either leads to interference fringes or not. This gives a solution to the problem of Wheeler's delayed choice experiment because now there is no such paradox as said by Wheeler "*Thus one decides the photon went through one path or both paths after it had already done its travel*" [7, 8] because the photon came through only one of the paths and as one places either a interference arrangement or a which-way detector changes the system in front of the photon and thus we have either interference or no interference.

Also the thought experiment shows that in a system whenever multiple paths are possible for the system to evolve, never means interference has to occur but only when the surrounding (in our case system is photon and surrounding is the apparatus) is favorable for interference. Also it shows that individual particles never occupy multiple states simultaneously, rather they are always in one state and it is the statistical nature of the system to have different particles in those states. It is the surroundings (apparatus) which statistically give rise to interference even if the photon moves in one path, but it causes different photons to take different paths such that an interference pattern is there.

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