The reality of de Broglie's pilot wave

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Abstract: In this paper we discuss a recent double-slit experiment where which-path information is obtained without disturbing the photons in their path to the detector, and, as a consequence, an interference pattern is observed on the far screen even if it is known which slit the photons go through. We argue that this result is in clear contradiction with a fundamental principle in orthodox quantum mechanics – Bohr's complementarity principle – and also point out that, on the other hand, the results of this experiment are the expected ones in the framework of de Broglie's pilot wave theory.

Keywords: pilot wave theory, orthodox quantum mechanics, Bohr's complementarity principle, double-slit experiment

1. Introduction

As is well known, if in a simple double-slit experiment with quantum particles a which-path measurement is made, i.e., if we observe which slit the particle goes through, then no interference pattern is observed on the far screen[1]. That is, it is not possible to have which-way information and an interference pattern at the same time.

According to orthodox quantum mechanics[2], this can be "explained" by applying Niels Bohr's complementarity principle[3]: the wave and particle pictures can never be observed at the same time, although both must be used if we want to obtain a full description of a phenomenon. This happens because the wave ψ that is divided into two as it reaches the double slit simply represents the probability of observing the corresponding particle in a certain state. The resulting waves ψ_1 and ψ_2 therefore represent the probability of observing the particle coming through the upper and lower slits, respectively, and so if we observe the particle just outside one of the slits then the wave going through the remaining one has to collapse, and so no interference pattern will appear on the screen.

One could, however, argue that such a measurement necessarily disturbs the particle whose state is being observed, e.g., by placing a detector just outside one of the slits, and thus it is natural to expect, even without invoking any particular principle, that the interference pattern is simply washed out. In fact, this simple and more intuitive explanation is the one obtained in the framework of the pilot-wave theory proposed by Louis de Broglie[4] in 1926. According to this approach the wave ψ actually exists as a physical entity, and guides its localized corpuscle – which carries almost all the energy in the particle and thus is able to trigger a detector – preferentially along a path where its intensity is higher. Therefore, as a particle reaches the double slit, the corpuscle takes only one of the paths but its guiding wave, which is divided into two, takes both. As a consequence, one of the resulting waves, ψ_1 or ψ_2, will travel alone towards the screen. In this situation, if a detector is placed just outside one of the slits then the wave going through it will either be absorbed or have its phase altered, and thus the interference pattern will naturally disappear.

In order to distinguish between these two points of view we would, therefore, need an experiment where which-path information is available but the particles going through the double slit are not disturbed in any way in their path to the far screen. Many different setups have been created in the last several decades to try and achieve this (see, e.g., the quantum eraser experiment[5] proposed in 1982) but none of them has actually succeeded, as in all the proposed schemes the particle's path is never free. In this paper, however, we will look at a recent, more sophisticated double-slit experiment where this requirement has finally been achieved, and where, as a consequence, an interference pattern is still observed. We will then argue that this result is in clear contradiction with orthodox quantum mechanics but is perfectly understandable if we take the point of view of the pilot wave theory.

2. A two-photon double-slit experiment

We will now present and discuss the double-slit experiment recently performed by Menzel, Puhlmann, Heuer and Schleich[6] in 2012 and repeated one year later[7]. The setup is shown in Fig. 1.

The source in this experiment is a UV pump beam composed of two distinct intensity maxima separated by a minimum at the centre. Therefore, each photon ψ can, as soon as it leaves the pump, be represented by a superposition of two waves, one corresponding to its upper maximum, ψ_1, and one representing its lower maximum, ψ_2.

The beam is injected onto a nonlinear crystal NL that transforms an incoming photon ψ into a pair of photons with half the frequency of the first – one called idler and represented by the wave ψ_i and the other one called signal, ψ_s. Only one pair of photons, correlated in space and time, is produced at a time. Thus, in this scheme each photon produced at the crystal can either be detected at its upper maximum or at its lower maximum, and so the wave-functions of the idler and signal photons can be written as $\psi_i = \psi_{i1} + \psi_{i2}$ and $\psi_s = \psi_{s1} + \psi_{s2}$, respectively.

The idler beam is directly incident onto detector D_i and the signal one is directed onto a double slit, in a way that the beam's upper maximum ψ_{s1} is injected onto the upper slit and its lower maximum ψ_{s2} is incident on the lower slit. The outcoming waves then are then incident onto detector D_s, which is scanned along a direction perpendicular to the signal photon's trajectory. The signal at D_s can then be counted in coincidence with the detections at D_i.

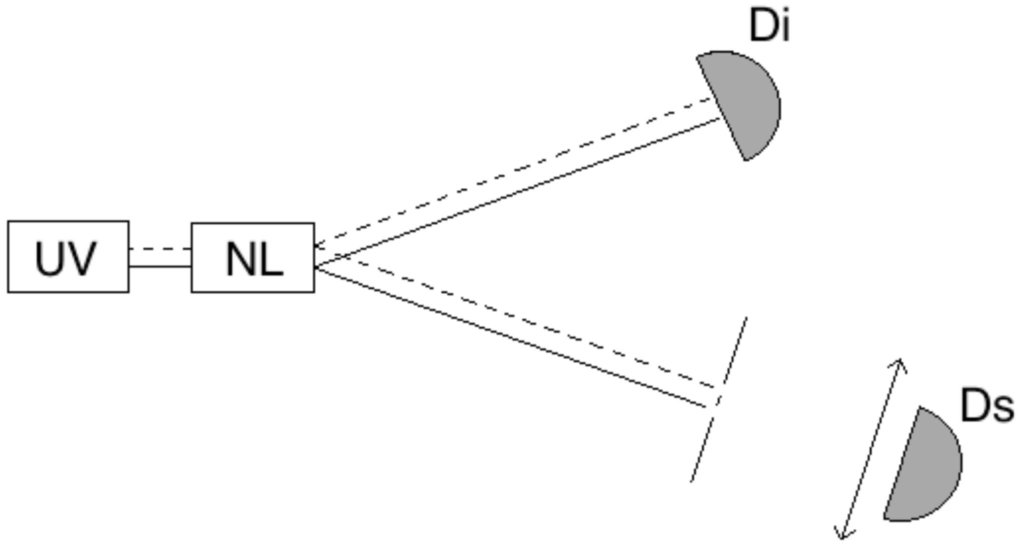

Fig. 1 – **Menzel *et al*'s double-slit experiment**: a UV pump beam is incident on a nonlinear crystal NL, which produces a pair of photons correlated in space and time. The idler (upper) photon is directly incident on detector D_i, whereas the signal (lower) photon goes through a double slit before reaching detector D_s.

Now, this experiment is divided in two parts. Detector D_s is first placed just outside the double slit for a near-field detection. In this case, the spatial correlation between the signal and the idler photons is observed: when an idler photon arrives through the upper maximum, which corresponds to the wave ψ_{i1}, a signal photon is detected in coincidence outside the upper slit, ψ_{s1}, and if an idler photon arrives through the lower maximum ψ_{i2} then a signal photon is detected outside the lower slit, ψ_{s2}.

D_s is then moved away from the double slit for a far-field detection. In this case an interference pattern is always observed when both slits are open, independently on whether the detections at D_s are counted alone or in coincidence with the ones at D_i, but disappears when one of the slits is closed.

We will now discuss the results from the point view of orthodox quantum mechanics and then in terms of the pilot wave theory.

2.1. Orthodox quantum mechanics

According to orthodox quantum mechanics, the photon ψ leaving the UV source is in a superposition of two states ψ_1 and ψ_2 corresponding to the equal probabilities of the particle being detected at the upper and lower maxima, respectively.

When the incoming photon arrives at the nonlinear crystal NL, an outcoming pair of idler ψ_i and signal ψ_s photons is produced in an entangled state. This means that if an idler photon is detected by D_i at the upper maximum then detector D_s will receive a corresponding signal photon through the upper slit, which will make the signal photon's wave-function collapse to its upper state, i.e., $\psi_s \rightarrow \psi_{s1}$, and when an idler photon is detected at the lower maximum a signal photon will be observed through the lower slit, which means that a collapse will occur to the lower state, $\psi_s \rightarrow \psi_{s2}$.

Now, as D_s is moved away from the double slit to allow for the far-field detection, measuring the position of the idler photon gives us the information about which slit the corresponding signal photon goes through. In this situation, as described above, the latter's wave-function will collapse to one of the upper or lower states, and thus $\psi_s \rightarrow \psi_{s1}$ if it comes through the upper slit or $\psi_s \rightarrow \psi_{s2}$ if it arrives through the lower slit. As a consequence, and contrary to the experimental results, no interference pattern should appear at the far screen.

In sum, the which-path information obtained due to the entanglement of the photon pair did not collapse the system's wave-function – which had to happen if the wave simply represented the probability of a particle being observed in a certain state – and so did not avoid the observation of an interference pattern. We have therefore shown that, in this particular case, there has been a clear violation of orthodox quantum mechanics, as Bohr's complementarity principle cannot be invoked in the way that it has been done in previous double-slit experiments.

2.2. Pilot wave theory

In a pilot-wave approach, each photon ψ emitted by the UV pump is composed of a corpuscle that is guided by a wave with two maxima, an upper one represented by ψ_1 and a lower one ψ_2. As the corpuscle leaves the source along the path of either maxima of its guiding wave $\psi = \psi_1 + \psi_2$, it will tend to remain there and avoid the intensity minimum at the centre of the wave, which means that the other maximum will travel alone towards the nonlinear crystal NL.

As the incoming photon enters the crystal, an idler photon ψ_i and a signal photon ψ_s are produced, each one composed of its own corpuscle and guiding wave with the two maxima now represented by ψ_{i1} and ψ_{i2} for the idler photon and by ψ_{s1} and ψ_{s2} for the signal photon. Moreover, each corpuscle produced will preferentially remain, as it travels along its path, in the same (upper or lower) maximum as the original one.

Now, when they both reach their corresponding detectors in the first part of the experiment, the idler and signal photons will naturally be detected at the same upper or lower maximum, which agrees with the experimental results. Note that only the corpuscles are able to trigger the detectors, as their respective waves do not carry enough energy to do so.

When detector D_s is moved away to the far field, in the second part of the experiment, the signal photon's wave ψ_s reaching the double slit will be composed of the same upper ψ_{s1} and lower ψ_{s2} maxima. Therefore, as both waves diffract when they leave the slits, it is obvious that an interference pattern will appear independently on whether we detect the signal alone or in coincidence with the idler photons. Naturally, if one of the slits is closed then the wave incident on it will be blocked and thus the interference pattern will disappear.

We thus see that, from the pilot-wave theory's point of view, it is easy to understand why an interference pattern can be present even if which-path information is available to the observer. Contrary to previous setups, in this particular one the particles going through the double slit have not been disturbed in any way in their path to the detector placed in the far field, and thus there is no reason for the interference pattern to be washed out.

3. Conclusion

In this paper we have shown that the experimental results obtained by Menzel *et al* are in clear contradiction with orthodox quantum mechanics, as in their setup the observation of an interference pattern after a double slit does not depend on whether which-path information is available to the observer. Thus, the incoming wave ψ that splits into two as it reaches the slits cannot simply represent a probability wave.

Moreover, we have made it clear why in this experiment, according to de Broglie's pilot wave approach, the interference pattern does not disappear when which-way information is available. Essentially, a simple and most natural explanation is that there is a real physical wave guiding the corpuscle along its path, and therefore there is no reason for the wave to collapse even if we know which slit the corpuscle goes through. Finally, if we accept that the wave is physical then it is as well natural that the interference does not occur when one of the slits is closed.

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