Has an Experimental Violation of Bohr's Complementary Principle been Observed?

Louis Groarke
Philosophy Department
University of Waterloo
Waterloo, Ontario
N2L 3G1

LeRoy Pazdernik
American University of Sharjah
P.O. Box 26666
Sharjah, United Arab Emirates

According to Bohr's complementary principle, one cannot simultaneously observe the wave-like and particle-like behaviours of a photon. This paper describes two experimental situations in which the complementary principle seems to be violated.

Key words: complementary principle, quantum theory, Niels Bohr, waves, particles

1. Introduction

The orthodox Copenhagen interpretation of quantum mechanics is based on Niels Bohr's complementary principle which stipulates that one cannot observe the wave-like and particle-like behaviours of a photon at the same time. Trajectories are considered to be particle effects; interference patterns are considered to be wave effects. Because we cannot observe particle and wave behaviours simultaneously, "we are presented with a choice of *either* tracing the path of a particle *or* observing interference effects." [1] One cannot identify a photon's trajectory while observing an interference pattern.

The complementary principle is believed to be a fundamental law of nature. [1-5, 9-12] It is widely believed that when light passes through a pair of slits, "it is impossible to determine through which slit each photon has passed without destroying ... the interference pattern."[3] There may be, however, situations in which one can identify which of a pair of adjacent apertures a photon passes through while preserving interference effects. In the present paper, we describe an empirical situation which constitutes an apparent violation of the complementary principle.

2. The Complementary Principle

We define Heisenberg's indeterminancy principle for a two-dimensional system as:

$$\Delta \vec{p} \cdot \Delta \vec{x} \geq \hbar, \tag{1}$$

where $\Delta\vec{p}$ is the uncertainty or change in the momentum of the particle, $\Delta\vec{x}$ is the uncertainty in the position of the particle, and $\hbar = h/2\pi$. According to the principle, we cannot simultaneously predict the future position and momentum of a particle with an accuracy greater than the prescribed amount. [4]

Consider next the argument advanced in support of the complementary principle by Ohanian and others [5]. Suppose we have a beam of coherent monochromatic light passing through two adjacent openings in an optical mask and falling on a distant screen in the usual manner. The incoming light will act in a wave-like fashion, producing an interference pattern on the distant screen.

Assuming that the distance to the screen is much larger than the slit separation, we can calculate the position of the resulting maxima according to a familiar formula from wave optics:

$$d\sin\theta = n\lambda \qquad n = 1, 2, 3, 4...; \tag{2}$$

where d is the slit separation and λ is the wavelength of the light.

Suppose we wish to determine through which of these two slits a particular photon passes. It is generally assumed that if we want to determine the location of the photon as it passes through the slits, we will have to introduce some additional experimental apparatus, say a Heisenberg gamma-ray microscope. Whatever the precise nature of the apparatus employed, it will have to measure the location of the photon with an uncertainty no larger than

$$\Delta y \cong d. \tag{3}$$

From relations (1) and (3), we get:

$$\Delta p_y \cong \frac{\hbar}{d}. \tag{4}$$

We know, however, that the momentum of a photon can be defined as:

$$p = \frac{h}{\lambda} \tag{5}$$

If the change in the angular deviation of the incoming photons is

$$\Delta\left(\sin\theta\right) = \frac{\Delta p_y}{p} , \tag{6}$$

it will follow, from relations (4) and (5), that this change must be

$$\Delta\left(\sin\theta\right) \cong \frac{\lambda}{d} . \tag{7}$$

But comparing relation (7) to equation (2), “we see that the uncertainty in the angle is as large as the angular separation between one maximum of the interference pattern and the next. Thus, the interference pattern will be completely washed out.”[5] Photons will strike the screen in a more or less random fashion and the interference pattern will be destroyed.

3. Physical Results

In this paper, we do not question the mathematical consistency of this argument. Instead, we will argue that we can create empirical situations in which the complementary principle, which is based on Heisenberg’s indeterminancy principle, appears to be violated. Physical familiarity with simple diffraction and interference effects calls the Copenhagen interpretation of these processes into question.

Our basic experimental apparatus consisted of a Neon laser ($\lambda = 632.8$nm), a shutter used to regulate photographic exposure, an adjustable metal slit, an optical mask made up of adjacent pinholes in a completely opaque film, and a photographic screen arranged in sequence on an optical bench. The first slit was used to enlarge the original beam. By narrowing the slit, one could create a diffraction pattern with a wide central maximum. One could then position the pinholes in this illuminated area and send the beam through very widely-spaced apertures (1mm $\leq$ pinhole separation $\leq$ 3.5mm). One obtains familiar diffraction and interference patterns with this arrangement. The utility of the slit is that it allows us to investigate interference phenomena produced by very widely-spaced apertures.

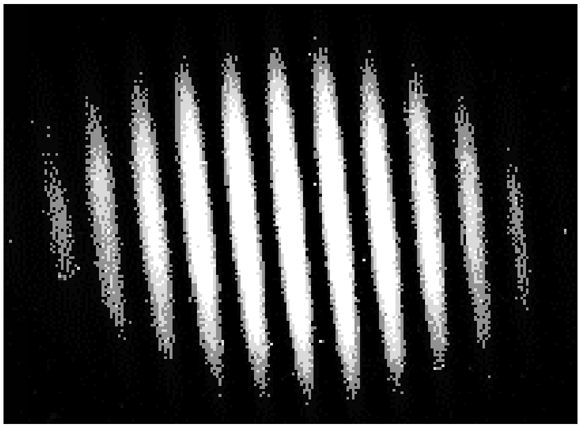

Figure 1: Close-up of cental region of pinhole interference pattern.

Suppose we shine the beam from our laser on a single pinhole made in our film and observe the pattern formed on a distant screen. We will observe the familiar Airy pattern, a series of concentric rings made up of alternating bright maxima and dark minima which echo the shape of the pinhole. [6] Suppose next that we shine the enlarged beam on two adjacent pinholes. In addition to the already described diffraction effect, we will observe an interference effect, two overlapping Airy patterns divided into a series of bright vertical fringes separated by darker minima. This vertically-striped pattern does not appear when we are dealing with single pinholes. It is only present when we have more than one pinhole. It is an authentic interference effect. Fig. 1* contains a close-up of some vertical fringes from the central region of one of these patterns.

Conventional optical theory attributes the vertically-striped fringing effects to the superposition of two or more light beams. [6] The present experiment conflicts with this conventional explanation, for in the case of very widely separated pinholes, one can produce interference effects even when there is very little or no overlapping of the light proceeding through adjacent pinholes.

The patterns displayed in Fig. 2 were created by laser light passing through a double pinhole mask. When one blocks out the right pinhole, the right side of the pattern is eliminated (Fig. 2A). When one blocks out the left pinhole, the left side of the pattern is eliminated (Fig. 2B). Fig. 2C demonstrates the interference pattern produced when light is allowed to pass through both pinholes at the same time. These results seem to indicate that photons moving through the right pinhole stay to the right and that photons moving through the left pinhole stay to the left. And yet one observes interference effects. Although we can, more or less, identify the pinhole through which photons on the right and left side of the pattern are passing, we, nonetheless, observe interference effects.

If the complementary principle stipulates that we cannot identify the pinhole through which photons are passing while preserving the interference effects, proponents of the principle generally assume that the only way we can identify the pinhole is by intervening in the experimental process with some sort of physical apparatus and perturbing the optical phenomenon. [12] One can, however, set up a situation in which such intervention is unnecessary.

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[*] The reproductions used in this paper were created by scanning the original laboratory photographs with a scanner. The resulting colour image was then converted to black and white.

Figure 2: Laboratory photograph of patterns produced by a pair of widely-separated pinholes with A) left pinhole illuminated, B) right pinhole illuminated, and C) both pinholes illuminated.

Fig. 3 contains photographs of patterns produced by very widely spaced pinholes. As can be verified by blocking out the light from individual pinholes, the beam of light on the right of Fig. 3A proceeds from the right pinhole, the beam on the left of Fig. 3A proceeds from the left pinhole. Although the middle region of the left beam has been overexposed, it is clear that both beams exhibit vertical interference fringing. Even though the light from the two beams is not superposed, we still obtain "interference" effects.

In Fig. 3B, a larger pinhole has been paired with a smaller pinhole. The light proceeding through the larger pinhole is on the left, the light proceeding through the smaller pinhole is on the right. Although the interference effects in the larger beam are only beginning to show, the smaller beam is clearly divided into five very distinct maxima. We know that the light in the right circular pattern has passed through the smaller right pinhole and yet we observe unmistakable interference effects.

According to the complementary principle, if we know the pinhole through which photons are passing, we cannot obtain interference effects. In these two cases, however, we do know the pinhole the photons in each beam of light are passing through *and* we observe, at the same time, interference patterns. This is not consistent with the complementary principle.

Proponents of the Copenhagen interpretation have responded to empirical challenges posed by extremely low-intensity interference phenomena [8], by arguing that each individual photon, on passing through adjacent apertures, interferes only with itself. [9-11] According to Louden, interference "can be achieved only if each photon passes partly through both pinholes." [11] The concept of "self-interference" is not only physically obscure. In the present instance, to suggest that a photon with a wavelength of approximately 0.6 mn passes simultaneously through two pinholes separated by a distance of over 3 mm seems especially tenuous. One can, however, provide a different demonstration of the apparent failure of the complementary principle.

In a second experiment, two adjacent pinholes, A and B, were positioned in the diffraction pattern produced by the first slit in our apparatus in the following manner. Pinhole A was placed inside the lighted central maximum of the diffraction pattern, whereas pinhole B was placed in a dark spot, in the middle of a minimum. In this kind of situation, pinhole A is illuminated, pinhole B is not. Visually inspecting the region immediately after the mask, one could observe no light passing

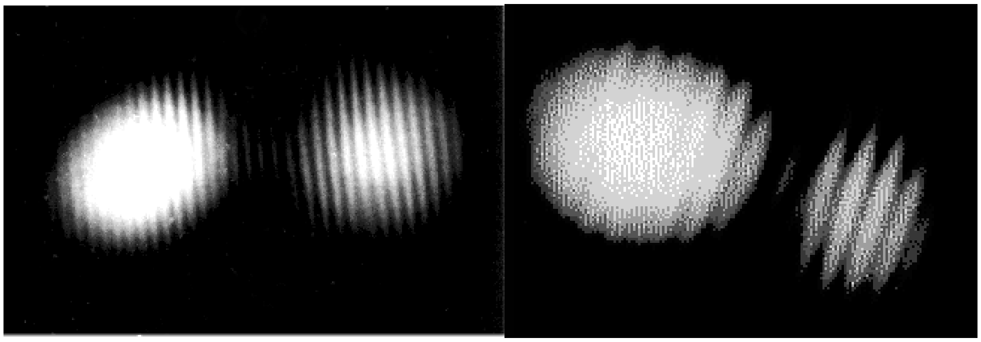

Figure 3: (A, B) Interference patterns produced by very widely-spaced pinholes.

through pinhole B. If, however, pinhole B is, for all intents and purposes, in a region of zero intensity, it will follow that all the photons reaching the screen pass through pinhole A. One can, however, use this procedure to obtain interference effects.

Fig. 4 includes photographs of two different pinhole patterns produced in the described manner. Because of the feeble illumination, the observed patterns were very dim. Nonetheless, they clearly displayed the vertical fringing effects peculiar to the interference process. Even if one can identify (with very high probability) the pinhole through which the photons are passing, one can still observe interference effects. This is not in agreement with the complementary principle.

4. Discussion and Conclusions

These preliminary results need to be corroborated. In the case of very widely-spaced pinholes, the observed phenomenon is clearly visible. When one of a pair of adjacent pinholes is placed in a minimum, the effects are more difficult to observe. In the latter case, the authors hope to redo the experiment, taking a precise physical measurement of the light intensity proceeding through the two pinholes so as to provide a quantitative rather than a purely qualitative argument.

Let us limit our discussion to two general points. In the experiments reported here, the observed interference effects do not appear to be caused by the physical superposition of two or more light sources. In the case of very widely-separated pinholes, light passing through the right pinhole makes up the right side of the pattern; light passing through the left pinhole makes up the left side of the pattern. Over a longer interval of time, light intensity may stray from one side to the other. One can, however, obtain interference patterns over much shorter intervals, even when there is no appreciable overlapping of light intensities. The Copenhagen interpretation of quantum mechanics insists on a literal interpretation of the interference process. This seems, in the present instance, problematic.

As Wesley has already argued, photons cannot cross over a region of zero intensity. [7] In the case of very widely-spaced pinholes, however, photons are divided up into bright maxima separated by dark regions, nodal surfaces of zero intensity, immediately after the mask. This suggests that photons traveling to the screen are confined to specific locations in space and follow identifiable trajectories rather than participating in the random, smeared out, trajectory-less process required by the Copenhagen interpretation of quantum mechanics.

According to the complementary principle, "There is no way in which one can simultaneously assign a photon to a particular pinhole *and* record the interference pattern." [11] Our data suggests

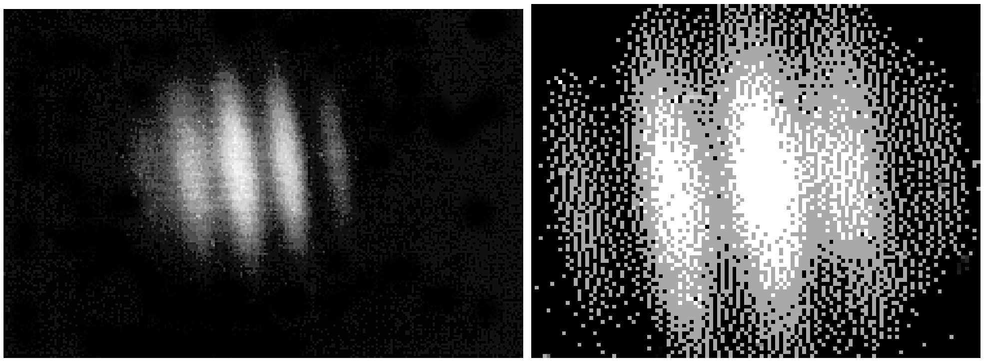

Figure 4: (A, B) Single pinhole interference patterns.

that we may be able to record an interference pattern even when we know (with very high probability) which pinhole the photon passed through. This would mean that one can, in principle, observe the wave-like and the particle-like behaviours of photons at the same time. Such results would lend credence to criticisms of the reigning Copenhagen interpretation of quantum mechanics proposed by authors such as Wesley. [7, 13-15]

Bohr's complementary principle is based on an "operationalism" which stipulates that physical knowledge is dependent upon on measurement and that measurement processes always necessitate some kind of obtrusive physical intervention.[16] As the present experiments demonstrate, however, we may be able to identify the pinhole without mechanically intervening and perturbing the optical phenomenon. [12] This calls for a more sophisticated view of epistemology, a project we will not pursue here.

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