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De Broglie Waves

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Abstract

There are many evidences in Quantum Mechanics about the existence of de Broglie waves: the two-slit experiment, self interference when a particle can follow two or more paths that converge, etc. There is not direct evidence of its existence because we use exclusively particle detectors. This paper presents a new evidence of the existence of de Broglie waves grounded in the action reaction principle. The action reaction principle is a fundamental ingredient of Physics: when two systems interact both change of state (*i.e.*, they depart from the free, isolated evolution path in the phase space). A simple experiment using a Mach-Zehnder interferometer is analysed. A representation of the evolution in the phase space for different cases (isolated system and interaction with a detector) is shown. By applying the action reaction principle we show that some subsystem, different from the corpuscular photon, must follow one arm of the interferometer when we can infer that the photon follows the other arm. There cannot be interaction between the photodetector in one arm and the photon following the other arm. This new subsystem would be a distributed de Broglie wave.

Subject Areas

Modern Physics

Keywords

Broglie Waves

1. A Mach-Zehnder Interferometer

In a Mach-Zehnder interferometer [1] [2], the beam of photons enters the apparatus through an initial beam splitter BS_i and it splits into two alternative paths (path α and path β). Through the corresponding mirrors (M_α and M_β) both beams converge again into a final beam slitter BS_f where they superpose and interfere (see **Figure 1**). The length of the arms of the

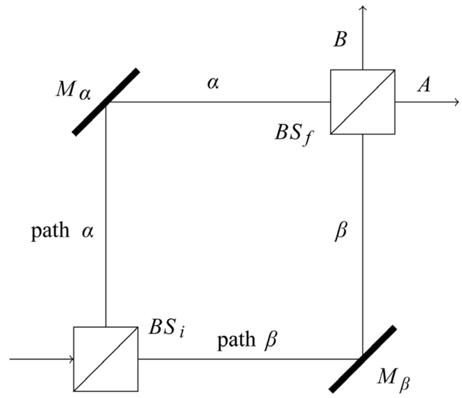

Figure 1. A Mach-Zehnder interferometer.

interferometer can be adjusted in such a way that all photons exit though gate A (100%), and this is the case even when the intensity of the beam is so low that each photon interferes exclusively with itself.

If we denote Ψ_0 the initial wave function of the particle, it splits into Ψ_α travelling through path α and Ψ_β travelling through path β. At the final beam splitter each component splits again into $\Psi_{\alpha A}$, $\Psi_{\alpha B}$, $\Psi_{\beta A}$ and $\Psi_{\beta B}$. The aforementioned adjustment means that $\Psi_{\alpha B} + \Psi_{\beta B} \equiv 0$, *i.e.*, there is destructive interference at exit B.

An Additional System

Let us introduce an obstacle (system 2 in **Figure 2**), for example a photodetector, in path α. Now there are three possible outputs: 1) the photon follows path α and it hits the photodetector (50%), 2) the photon follows path β (with a final wave function $\Psi_{\beta A} + \Psi_{\beta B}$, Ψ_α is discarded because path α is blocked) and it exits through gate A (25%), 3) the photon follows path β and it exits through gate B (25%).

2. Evolution in the Phase Space

We can consider the phase space Ph_1 of system 1, with five distinguished macrostates (see **Figure 3**):

1. Photon at position 0, initial around BS_i.
2. Photon at position α, a point along the path α.
3. Photon at position β, a point along the path β.
4. The photon quits the interferometer through gate A.
5. The photon quits the interferometer through gate B.

2.1. Free (Isolated) Evolution of System 1

The initial state is the photon at position 0 and the final state is the photon at position A, symbolically $0 \to A$ (**Figure 3**). We do not have information about the specific evolution path from 0 to A, in particular we ignore if the photon has followed path α or β or something different.

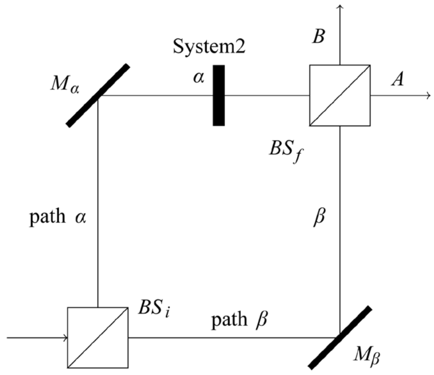

Figure 2. The interferometer with an obstacle (system 2).

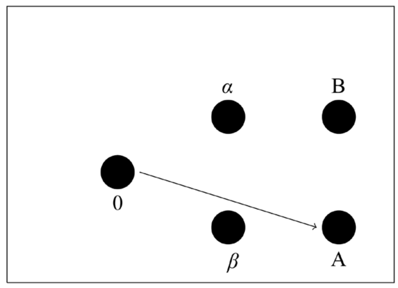

Figure 3. Phase space Ph_1 of system 1. Some distinguished macroscopic states (spatial locations of the photon) are shown. Free (isolated system) evolution.

2.2. Interaction with System 2, a Photodetector

As we have seen there are three possible evolution paths at Ph_1 under interaction with system 2:

1. $0 \to \alpha$ (**Figure 4**). 50% of the runs.
2. $0 \to \beta \to A$ (**Figure 5**). 25% of the runs.
3. $0 \to \beta \to B$ (**Figure 6**). 25% of the runs.

In case 1 we can state the final position of the photon at α because of the presence of the photodetector (system 2), that gives a macroscopic response when hit by the photon. The action reaction principle is fulfilled, both systems change of state with regards to their free, isolated evolution.

Similarly, in cases 2 and 3, as there is negative detection at α (system 2 does not change of macroscopic state) we can infer that the photon has followed path β. It arrives to exit gate A (case 2) or B (case 3), where it is detected by photodetectors adequately positioned. Is the action reaction principle fulfilled?

2.3. Case 3

The last case (3) is the one of our interest. It is explicit the change of evolution with regards to the free case, symbolically $0 \to \beta \to B$ instead of $0 \to A$.

According to the action reaction principle this departure from the free (isolated) evolution path must be accompanied by a change of state of system 2. But a photodetector does not show a macroscopic change of state, the photon

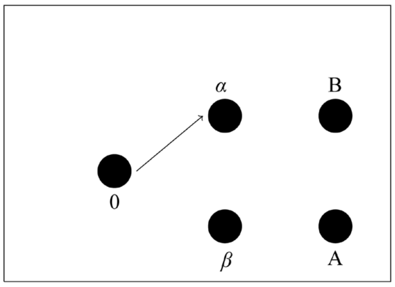

Figure 4. Interaction. Case 1: photon detected at α by system 2.

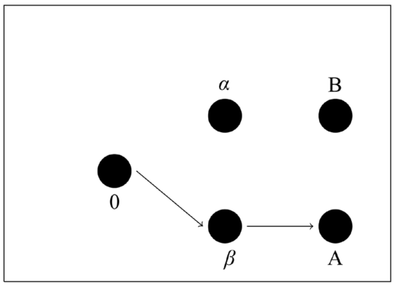

Figure 5. Interaction. Case 2: photon detected at A.

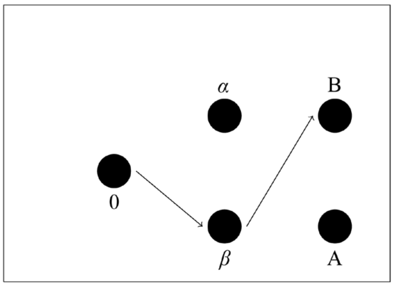

Figure 6. Interaction. Case 3: photon detected at B.

does not interact with system 2. We should use a different apparatus, able to show a macroscopic change of state when interacting with some unknown subsystem that follows path α and interacts locally with system 2. This subsystem is possibly a distributed wave, not a corpuscular entity. There is certainly not interaction at a distance between the photon following path β and system 2 located at α, they are relativistically separated.

System 1 is then a composite of the interferometer, a corpuscular subsystem (the photon) and a wavelike subsystem (the accompanying wave).

2.4. Phase Space of the Photodetector

In case 1 of the interaction there is a macroscopic change of state in the photodetector: the photon follows path α and hits the photodetector, system 2. The photomultiplier generates a cascade of photons that becomes macroscopically observable (Figure 7).

In cases 2 and 3 of the interaction the photon follows path β and does not interact with the photodetector, so that there is not macroscopic change of state in it. However, if the action reaction principle is fulfilled there must be a microscopic change of state in system 2 (Figure 8). A different apparatus could show a macroscopic change of state.

The same experimental set up was considered in [3]. There, the authors also understood that the action reaction principle was apparently violated. Their solution to this incoherence was to consider the Many Worlds interpretation of Quantum Mechanics. In that interpretation, there was a reaction in the other branch, the other world, were the photon follows path α, so that considering both branches simultaneously there was fulfillment of the action reaction principle. However, in the other branch there is both an action and a reaction (local interaction of the photon and the photodetector), so that considering both branches, worlds, together we get two actions and only one reaction, which seems unsatisfactory to me. We can recover the action reaction principle with just one world if there is a (not yet detected) change of state of system 2, located in path α, when the photon follows path β. While the Many Worlds interpretation is not a scientific approach, it cannot be confirmed or rejected

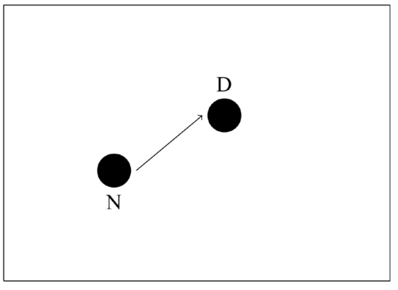

Figure 7. Phase space of system 2. Case 1: detection of the photon at α. N denotes the initial (null detection) state, and D denotes the detected photon state.

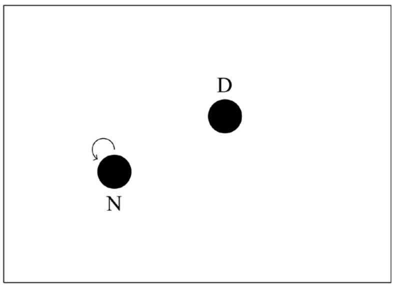

Figure 8. Phase space of system 2. Cases 2 and 3: the photon follows path β and is not detected. According to the action reaction principle there must be a microscopic change of state in system 2; however, the macroscopic state N does not change.

from experimental measurements, the description I am proposing here is scientific: some apparatus could detect a wave like signal arriving to system 2, so that it can be confirmed, or rejected as far as no change of state is detected in system 2.

3. The Two-Slit Experiment

The two-slit experiment is another fundamental proof of the existence of de Broglie waves. It works with both photons and massive particles as electrons; electrons show a wave-like character in different experiments [4].

When we install particle detectors behind both slits we find that the particle always goes through one or the other slit, never through both or any other way. As the particle cannot "know" before crossing the slits if there are or there are not detectors we can infer that the same behaviour happens, the particle going through one or the other slit, when no detectors are installed.

There is no diffraction pattern when one of the slits is closed. Therefore, some subsystem must follow this, or better both slits, a wave like system that generates the diffraction pattern when both slits are open. The de Broglie waves act as guiding waves for the particle, and after many runs in which each particle creates a spot on the final screen we obtain the reproduction of the wave like diffraction pattern.

4. Conclusions

We can conclude that:

1) The action reaction principle (a fundamental law of Physics) predicts a change of state of system 2, even when the photon follows path β and does not interact with system 2. It is a challenge to design an apparatus able to enhance the change of state of system 2 into macroscopic scale.

2) Some system, associated to the photon (corpuscular), must follow path α when the photon follows path β, in order to interact with system 2. I conjecture that this system is wave-like. We could denote this accompanying wave a de Broglie wave [5]. It would facilitate, for example, a rational explanation of the two-slit experiment.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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