Particle Mediated Quantum Effects

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We analyze an experiment that consists of two statistically independent laser beams that cross, separate and end at detectors. At the beam intersection there is a thin wire at the center of a presumed dark interference fringe. Since photon count at end detectors is similar with or without the wire in place, wave visibility is maximum $V \approx 1$. With the wire at the center of a dark fringe, classical wire diffraction is insignificant; thus, photons maintain their direction, which implies that there is a high level of particle which-way information, $K \approx 1$. Since $K^2 + V^2 \approx 2$, it appears that the complementarity inequality, $K^2 + V^2 \leq 1$, is violated. We find that there is no violation provided that virtual particles are included in the analysis of the complementarity inequality. We propose that virtual particles are a key component of the mechanism that explains how quantum effects work.

Keywords: Virtual particles, complementarity principle, particle-wave duality, interpretation of quantum mechanics, Afshar experiment

Introduction

Most researchers are convinced that strong, weak and electromagnetic interactions are mediated by particles [1,2]. Particles come in two energy-momentum states, on-shell and off-shell. On-shell particles are those that fulfill the energy-momentum relation for free particles, $E^2 = p^2 c^2 + m^2 c^4$. On-shell particles could propagate to infinity. Off-shell particles, also known as virtual particles, do not fulfill the energy-momentum relation for free particles; thus, they cannot be set free. Virtual particles are short-lived and appear between interacting particles. Virtual particles have peculiar properties. Even though the charm quark has mass heavier than the proton mass [3], the proton appears to contain virtual charm quarks. Virtual particles could transfer energy-momentum in such a way that their net effect could be either a push or a pull. Besides transferring energy-momentum, virtual particles can transfer discrete units of angular momentum and charge. Interactions mediated by virtual particles obey the conservation laws. The most studied physical effects that are attributed to virtual particles are scattering and bound states.

The Dirac equation makes accurate predictions for the hydrogen atom without appealing to virtual particles. This is true because the proton is much heavier than the electron [2]. However, when the masses of the bound state particles are comparable, such as in the electron-positron atom, the correct solution is based on a technique that requires the exchange of large number of virtual particles [4]. Even in the hydrogen atom, subtle effects such as Lamb’s shift require the introduction of virtual particles [2]. Now we believe that in the hydrogen atom, electron and proton are held together by constant exchange of virtual particles. Virtual particles transfer energy-momentum so that the electron would fulfill the conditions of the wavefunction. Consider the electron in hydrogen with quantum numbers $n = 4$, $l = 1$, $m = 0$; the corresponding radial probability density displays a pattern with high and low intensities regions. Thus, virtual particles must drive the electron out of regions with low intensity and towards regions with high intensity. These high and low intensity regions are similar to bright and dark fringes in an interference pattern. In this paper we study how the accumulation and exclusion of photons in the formation of bright and dark interference fringes must be mediated by virtual particles if the complementarity inequality is to be upheld.

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Following the work of Wheeler, we associate which-way information, $K$, with the degree to which we could identify the origin of a particle by applying momentum conservation [5]. Once we determine where a free particle ends and know its direction, then momentum conservation allows us to infer where the particle originates. If we could determine where a particle originates then we have maximum which-way information, $K = 1$. If we could not identify the origin of the particle, we have zero which-way information, $K = 0$. We could also have partial which-way information, $1 > K > 0$.

Visibility, $V$, measures the contrast between bright and dark fringes in an interference pattern formed by accumulation of particles. If we could determine that a particle fully avoids a given region and is attracted to an adjacent region then its visibility is maximum, $V = 1$, since it contributes to the formation of adjacent dark and bright fringes. On the other hand, if we determine that the particle is equally likely to reach any place within a region then its visibility is zero, $V = 0$, since it contributes to the formation of a uniform distribution. We also could have partial visibility, $1 > V > 0$.

Which-way information, $K$, is a particle property and visibility, $V$, is a wave property. The values of the $K$ and $V$ are limited by Bohr’s principle of complementarity. Particle-wave complementarity is summarized by the inequality [6,7]

$$K^2 + V^2 \leq 1.$$  

We note that it is not always possible to directly measure which-way information and visibility. When we cannot directly measure either of these parameters, we use indirect ways such as applying the conservation laws [5].

**Experiment with independent laser beams**

We analyze an experiment [8] that consists of two statistically independent laser beams in phase that cross at small angle, separate and end at detectors as in Fig. 1. The beams have a Gaussian profile. The experiment could be run at a photon count so low that at a given time there is high probability that only one photon is present in the entire setup [8]. It is possible to replace the independent laser beams with two independent lasers as sources 1 and 2 [9,10].
**Fig. 1 Two independent laser beams intersect and end at detectors.** When detector 1 clicks, we infer that the photon came from source 1; thus, we have maximum which-way information, $K = 1$. At the beam intersection, the electric field interferes constructively and destructively as the pattern in blue and grey shows. Each beam has a Gaussian profile shown in yellow.

In the experiment in Fig. 1, the electric field intensity produced by two plane waves with momentum components $\mathbf{p}_1$ and $\mathbf{p}_2$ that cross at small angle $\alpha$ is given by $E_0^2 \left( 1 + \cos\left[ 2\pi \frac{\alpha y}{\lambda} \right] \right)$, where $y$ is a location transverse to the beams and $\lambda$ is the wavelength [11]. Thus, at the beam intersection the electric field shows constructive and destructive interference fringes. When an opaque screen is placed at the beam intersection, we observe interference fringes with maximum visibility, $V = 1$. At the classical level these fringes are real whether or not we observe them. In addition, when a detector clicks, we infer the source of the photon uniquely and the which-way information is maximum, $K = 1$. Therefore, at the classical level, experiment in Fig. 1 presents a violation of the complementarity inequality in Eq. 1.

Instead of using an opaque screen that blocks the beams the authors of the experiment [8] use a relatively thin wire, which is 12.5 times thinner than the distance between consecutive bright or dark fringes [12]. First, they consider the case with the beams crossing freely and establish the photon count at one of the end detectors. Then, under similar conditions, the 17 $\mu$m thick wire is scanned across the beam intersection. The ratio $(f)$ of photon count with wire in place over the photon count without wire is plot in Fig. 2. The solid line is a calculation of $f$ using Fraunhofer diffraction [8v2]. Theoretical and experimental results are in excellent agreement.
According to Fig. 2, when the wire is at 0.6 mm the fractional photon count drops to 0.88, which indicates a 12% decrease in photon count [8]. This implies that there is a bright fringe at 0.6 mm and that the wire is thick enough to stop and scatter 12% of photons. On the other hand, when the wire is at 0.7 mm the fractional photon count is nearly one which implies that the wire acts as if it were invisible. If a photon avoids the wire, then the photon intensity at the wire is zero, $I_0 = 0$. This photon must be deflected away from the wire to an adjacent region where the intensity must be different from zero $I \neq 0$. This implies that the visibility for this photon is close to 1, $V = \frac{I - I_0}{I + I_0} \approx 1$.

A calculation using Fraunhofer diffraction [8v2,11] shows that when the wire is at the center of a dark fringe, wire diffraction is insignificant. This is so because at the center of a dark fringe there is hardly any field to diffract. Insignificant wire diffraction implies that a photon that comes from source 1 most likely ends at detector 1 and only an insignificant number of photons that come from source 1 will end at detector 2. Thus, according to classical physics, the photon that comes close to the wire but avoids it maintains a high level of which-way information, $K \approx 1$, and a high level of visibility, $V \approx 1$. Similar results were also obtained in the Afshar experiment [12]. Therefore, we have uncovered a second violation of the complementarity inequality in Eq. 1, at the classical level.

**Paradox resolved**

We concentrate on the case where the wire is located at 0.7 mm. According to experimental data, when there is no wave interference at the beam intersection, the wire located at 0.7 mm causes a drop of 5% of the total number of photons [8v2]. However, when there is wave interference at the beam intersection and the wire is at 0.7 mm, practically all the photons avoid being absorbed or scattered by the wire. This is as if a repulsive force field were generated by the charges in the wire. The interaction at a distance between a photon and the potential (force field) generated by a charge is known as Delbruck scattering [13-15]. The corresponding Feynman diagram is displayed in Fig. 3b. This interaction requires a virtual electron loop that interacts with the incoming photon, outgoing photon and two virtual photons. The virtual photons mediate a force between the virtual electron in the loop and the charge in the wire.
Fig. 3. Lowest order Feynman diagrams for particles interacting with a potential denoted by an x. a) An electron in hydrogen exchanging a virtual photon with the proton. As a result, the electron changes momentum. b) A photon scatters from the potential produced by a charge in the wire. This interaction requires a closed virtual electron loop. Two virtual photons are exchanged between the electron in the loop and the charge in the wire; thus, a positive or negative charge in the wire will produce the same probability amplitude.

Delbruck scattering amplitude is proportional to the square of the charge in the wire; thus, the photon interacts equally with positive and negative charge in the wire. The cross section for this interaction is small. However, the wire is an object with a macroscopic number of charges and the photon could interact with any number of charges; this possibility can increase the net strength of the interaction so that the dark fringe could be formed.

Virtual particles materialize the intricacies of the electron states in the hydrogen atom. The overall effect of virtual particles in hydrogen is to make it likely to find the electron in regions of high probability density and make it unlikely to find the electron in regions of low probability density. The probability density is directly related to the magnitude of the wavefunction. The necessary momentum to drive the electron is provided by the proton and transferred by virtual photons. Similarly, virtual particles could materialize the intricacies of interference and diffraction of light. For the setup in Fig. 4, at the vicinity of the wire, the regions with high electric field intensity are adjacent to the wire and along the two outgoing beams. On the other hand, the region with low intensity is at the wire. Thus, that 5% of photons, that are lost in the absence of interference, are prevented by virtual particles to be absorbed by the wire and are led instead to one of the two outgoing beams.
Fig. 4 Photon deflection from a wire at the center of a dark fringe. A photon from source 1 heads towards the wire, located at the center of a dark fringe, but avoids it. This photon collaborates with the formation of a dark fringe; thus, it has high level of visibility, \( V = 1 \). After the wire, there are two equally likely possibilities for the photon: a) beam 2 with momentum \( \vec{p}_2 \) and b) beam 1 with momentum \( \vec{p}_1 \). Thus, when a detector clicks, we cannot infer from which source the photon came and its which-way information is zero, \( K = 0 \). The necessary momentum for all these maneuvers is provided by the wire and transferred by virtual particles.

Since a given photon avoids the wire and is attracted to an adjacent region, its visibility is maximum, \( V = 1 \); this photon contributes to the formation of adjacent dark and bright fringes. The photon that passes the wire is faced with two outgoing beams with identical electric field intensity; thus, the photon is randomly driven by virtual particles into one of the two beams. The random distribution of photons into one of the beams erases which-way information, \( K = 0 \), as it makes it impossible for momentum conservation to reveal whether the photon came from source 1 or 2. According to this mechanism, photon count at the end detectors remains unchanged just as it is experimentally observed. At the wire, the visibility is one and the which-way information is zero. The complementarity inequality in Eq. 1 is preserved.

In the case when an opaque screen is placed at the beam intersection, the incoming photon requires momentum so that it would go from uniform Gaussian profile to a Gaussian profile with interference fringes. In this case the momentum necessary for photon deflection would be provided by the charges that form the opaque screen; momentum would be transferred by virtual particles.

We note that if there is no external object to provide momentum, then photons could not be deflected regardless of the state of the electric field. For instance, when photons cross the beam intersection unhindered as in Fig. 1, they maintain their original momentum from source to detector. At the beam intersection the electric field displays interference fringes but photons cannot fulfill this pattern as there are no external sources to provide the required momentum. Since the uniform beam profile for these photons is unchanged throughout their entire path, their visibility is zero. Thus, these photons have full which-way information, \( K = 1 \), and zero visibility, \( V = 0 \); the complementarity inequality is not violated either.

**Concluding remarks**

In the experiment analyzed here, when the wire is at the center of a dark fringe, classical wire diffraction is insignificant. According to classical physics, the presence of the wire at a dark fringe, hardly deflects
light from its original path. On the other hand, according to the mechanism introduced here, the dark fringe is materialized by an interaction mediated by virtual particles. This interaction must be large enough to deflect photons that come close to the wire. Once these photons are deflected, they are given the precise momentum to randomly take one of the two beams. We note that it would be impossible for classical wire diffraction to perform the tasks we attribute to virtual particles. Particularly, classical physics is deterministic and would not produce the random distribution of photons necessary to erase which-way information and save complementarity.

We find that the dynamics of a photon when it passes by macroscopic objects depends on virtual particles transferring energy-momentum from a given source to the photon so as to materialize the expectation indicated in the electromagnetic field. Thus, momentum conservation alone determines the path of a free photon regardless of the state of the field associated with the photon. This physical property that applies to the photon should apply to the electron and other particles.

The interaction that involves virtual particles is enhanced when the particle is near macroscopic objects. This is due to the fact that macroscopic objects have a macroscopic number of sources. Even if the basic interaction is weak, the particle could interact with many components of the macroscopic object resulting in the effect expected by quantum theory.

The photon and the two beams experiment is related to the particle and two slits experiment discussed by Richard Feynman who made the comment [16]: “We choose to examine a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the only mystery.” Our analysis of the photon and the two beams experiment shows particle-wave paradoxes that cannot be explained with classical physics. However, a quantum analysis based on virtual particles shows that there are no paradoxes or violations. According to Feynman’s comment, if a mechanism could explain the particle-wave paradox, then the same mechanism would explain other mysteries in quantum mechanics.

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