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Quantum Entanglement and Young's Experiment

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Abstract

Bohm's variation of the Einstein-Podolsky-Rosen thought experiment may reveal the path a photon travels in Young's experiment without causing the interference pattern to disappear. Unlike in Young's original experiment, this hypothetical scenario involves entangled photons incident on a screen with two closely spaced narrow slits. To address the challenge of simultaneously observing both the wave and particle nature of light without violating Heisenberg's position-momentum uncertainty principle, an apparatus that relies on the conservation of linear momentum and quantum entanglement is constructed to indirectly observe the path traveled by the entangled photons while preserving their quantum superposition. This thought experiment effectively uncovers the complex mystery surrounding the wave-particle duality inherent in quantum phenomena.

Keywords

Entanglement, Wave-Particle Duality, Double-Slit, Which-Path Information, Quantum Superposition

1. Introduction

Physics of the extremely small has confounded physicists for little over a century. Quantum mechanics is the mathematical machinery developed in the mid 1920's by physicists such as Werner Heisenberg, Erwin Schrodinger, and Max Born [1]-[3] to name a few, to describe the strange and perplexing phenomenon that has come to be known as the wave-particle duality [4] [5] of nature. Richard Feynman, in his admirable introduction to quantum mechanics [6], notes that this wave-particle dual behavior contains the basic mystery of quantum mechanics. In fact, he goes so far as to say: "In reality it contains the only mystery".

Thomas Young's seminal double-slit experiment [7] is one of the most notable experiments that clearly displays the wave-particle duality of nature, especially in the case for individual particles passing through the apparatus one at a time. The interference pattern produced by particles passing through two closely spaced narrow slits vanishes if one tries to observe which slit the particle traveled through to produce the observed interference pattern. According to quantum theory, observation of the path of the particle without causing the interference pattern to vanish is prohibited by Heisenberg's position-momentum uncertainty principle. In this study, we propose a novel thought experiment that relies on conservation of linear momentum and quantum entanglement [8] to reveal the which-path information of the incident photons without disrupting the interference pattern.

2. EPR-Bohm Thought Experiment with Photon Pairs

Albert Einstein, Boris Podolsky, and Nathan Rosen meant to look for an experiment that could measure, indirectly but simultaneously, two mutually exclusive quantities like position and momentum. Such results would contravene the predictions of quantum mechanics, which allows the measurement of only one such quantity at a time; that is why this thought experiment has come to be known as the EPR paradox [9].

In 1952 David Bohm showed that the paradox could be set up not only with continuously varying quantities like position and momentum, but also with discrete quantities like spin. Thus, let us consider the EPR-Bohm thought experiment for photon pairs [10]. Suppose a light source S at rest with zero spin spontaneously emits two photons simultaneously. In accordance with the conservation of linear momentum, the two photons diverge from S in opposite directions at the same speed [11], as shown in **Figure 1**. Since the initial total spin angular momentum of the system is zero and must be conserved, then the final total spin angular momentum of the system is zero, as well.

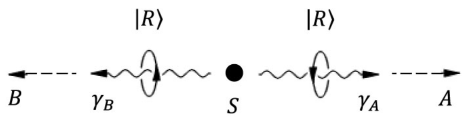

Figure 1. A particle S with zero momentum and spin decays into two photons γ_A and γ_B, which conserve total linear and spin angular momentum.

According to quantum mechanics, we can arrange our light source so that each emitted photon pair occupies a quantum state known as a singlet or spin singlet state. The photons of a photon pair are thus said to be entangled or correlated. This can be viewed as a quantum superposition of two states, which we shall call state $|R\rangle$ and state $|L\rangle$, for photons with right and left-handed spin, respectively. This is a state of entangled spin angular momentum. Because circular polarization is assigned relative to the direction of propagation, the singlet state of the two counter-propagating entangled photons denoted γ_A and γ_B, respectively includes two right-handed spin $|R,R\rangle$ and two left-handed spin $|L,L\rangle$

photons, which are states of zero total angular momentum [12].

Let us assume that in state I, γ_A and γ_B each have right-handed spin; and in state II, γ_A and γ_B each have left-handed spin. Hence, the quantum state occupied by each photon pair emitted by our spin-zero source is described by the following relation [12]

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|R,R\rangle + |L,L\rangle\right),$$

where $|R,R\rangle$ is the state vector for state I and $|L,L\rangle$ is the state vector for state II. In general, the singlet state for photons is symmetric in the circular polarization basis and exhibits perfectly correlated spin components when locally measured along any axis.

3. Young's Experiment with Single Photons

The acceptance of the wave character of light was firmly established in 1801, when the English physicist and physician Thomas Young demonstrated optical interference with his now classic two-slit interference experiment. In Young's experiment, sunlight was passed through a pinhole on a board. The emerging beam fell upon two pin holes, separated by a few millimeters, on a second board. The light emanating from the two pinholes then fell on a screen where a pattern of bright and dark spots was observed [7]. This pattern, called fringes, can only be explained through interference, as a wave phenomenon. Today, aware of the physics, we generally replace the pinholes with narrow slits that let through much more light.

Over one hundred years later in 1909, Sir Geoffrey Ingram Taylor, while an undergraduate, set up Young's experiment and gradually reduced the intensity of the incident light beam to such an extent that there would only be one quantum of energy (a single photon) in the apparatus at any given instant [13]. The resulting interference pattern was recorded using a photographic plate with a very long exposure time. To his disappointment, he found no noticeable change in the pattern, even at the lowest intensities.

At this point one may naturally ask, doesn't it take two waves to interfere? Can a single photon split in half, pass through both slits simultaneously, and then interfere with itself? Quantum mechanics unambiguously says yes. As Paul Dirac, one of the pioneers of relativistic quantum field theory, put it: "Each photon interferes only with itself. Interference between different photons never occurs" [14]. The proof that quantum mechanics offers for this absurd proposition is known as the principle of quantum superposition [8]; and has no classical analogue. Quantum superposition is supposedly responsible for all the miraculous magic that quantum systems are capable of, which have been completely verified by a myriad of experiments and modern technologies.

We must not get carried away and conclude from the interference pattern that photons are classical waves, because photons do arrive at the photographic plate in a definite way—one localized flash per photon. It is the totality of spots made by many photons that forms the wave interference phenomena. Analogous to electron waves, photon waves are probability (or relativistic de Broglie) waves [5] [6]. Hence, we say that the probability of a photon arriving at the light areas on the detection screen is high while the probability of a photon arriving at the dark areas is low. Accordingly, the corresponding state of the photons exiting the two slits is represented by the following expression:

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\psi_1\rangle + |\psi_2\rangle\right),$$

where $|\psi_1\rangle/\sqrt{2}$ and $|\psi_2\rangle/\sqrt{2}$ represent the (normalized) probability amplitudes for a photon to pass through either slit 1 or slit 2, respectively.

4. Young's Experiment with Entangled Photon Pairs

Let us imagine that a spin-zero source decays and emits entangled photon pairs [15] with one photon of the entangled pair traveling in direction A and the other traveling in direction B (see **Figure 2** for reference). The geometry is determined by lenses so that the source is effectively a point. Photons traveling in direction A are incident on a screen with two closely spaced narrow slits to form a coherent superposition of $|\psi_r\rangle$ and $|\psi_l\rangle$. The slits along with conservation of linear momentum confine the escaping decay particles to either of a pair of opposite directions, defined in **Figure 2** as r and r' or l and l'. Thus, we can write the state of the two-particle system as

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\psi_r\rangle|\psi_{r'}\rangle + |\psi_l\rangle|\psi_{l'}\rangle\right),$$

where the subscript letters denote the escape directions of the entangled photon pairs imposed by the corresponding slits. This expression combines the various elements of the system in a non-separable [16] manner which explains the observed correlations.

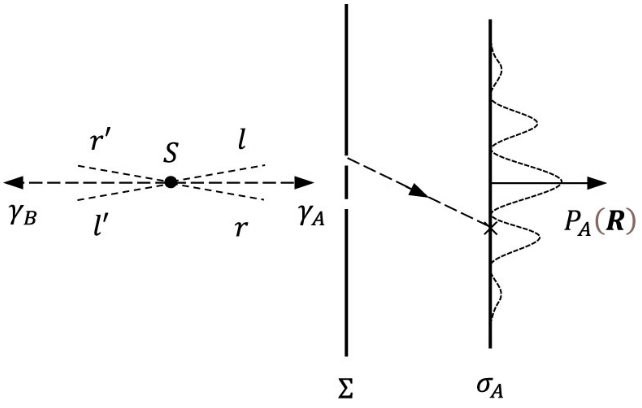

Figure 2. Entangled photons γ_A emitted by a spin-zero light source S pass through screen Σ with two narrow slits to produce an interference pattern on detection screen σ_A [17].

The probability density for γ_A arriving at a point $\boldsymbol{r} = \boldsymbol{R}$ on the detection screens σ_A is given by the squared modulus of $\psi_A(\boldsymbol{R})$, that is

$$P_A(\boldsymbol{R}) = \left|\langle \boldsymbol{R}|\psi\rangle_A\right|^2 = \frac{1}{2}\left[\left|\psi_r\right|^2 + \left|\psi_l\right|^2 + \psi_r^*\psi_l\psi_{r'}^*\psi_{l'} + \psi_l^*\psi_r\psi_{l'}^*\psi_{r'}\right].$$

But because $\psi_{r'}^*\psi_{l'}$ and $\psi_{l'}^*\psi_{r'}$ do not vanish, the cross-terms $\psi_r^*\psi_l$ and $\psi_l^*\psi_r$ responsible for the usual interference phenomena observed at σ_A [18] [19], are not canceled out.

5. Indirect Observation of Position

Now we consider the situation where detection screen σ_B is added to the apparatus, as shown in **Figure 3**. Because the distance from the light source S to detection screen σ_B is greater than the distance from S to σ_A, the photons γ_B arrive at σ_B after their partner photons γ_A reach σ_A. Consequently, the interference terms $\langle \psi_r|\psi_l\rangle$ and $\langle \psi_l|\psi_r\rangle$ are collapsed, so that the probability density for γ_B arriving at a point $\boldsymbol{r} = \boldsymbol{R}$ on the detection screen σ_B is given by the squared modulus of $\psi_B(\boldsymbol{R})$, without any interference terms

$$P_B(\boldsymbol{R}) = \frac{1}{2}\left(\left|\psi_{r'}\right|^2 + \left|\psi_{l'}\right|^2\right),$$

where $\left|\psi_{r'}\right|^2 = \left|\psi_r\right|^2$ and $\left|\psi_{l'}\right|^2 = \left|\psi_l\right|^2$, which satisfies conservation of linear momentum.

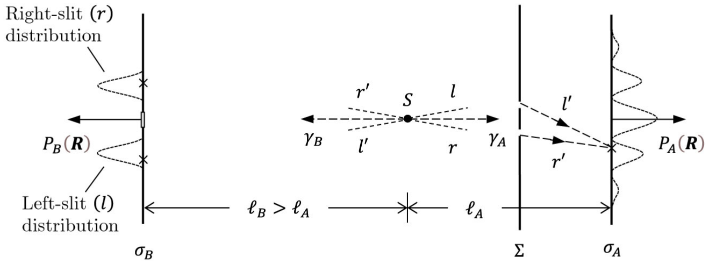

Figure 3. Observation of where photons γ_B land on detection screen σ_B reveals the position of its partner photon γ_A without disturbing the interference pattern on detection screen σ_A.

After a photon is detected at σ_A its corresponding entangled partner is detected at σ_B. If the photon detected at σ_B lands on the right-slit distribution (as labeled in **Figure 3**), then in accordance with the conservation of linear momentum, the photon γ_A must have traveled through the right slit to arrive at the detection screen σ_A. However, if the photon γ_B lands on the left-slit distribution, then in accordance with the conservation of linear momentum, γ_A must have passed through the left slit to produce the interference fringes observed at σ_A. Hence, in theory, our apparatus allows one to indirectly observe position while preserving quantum superposition.

6. Conclusions

This study demonstrates that by applying conservation of linear momentum to

Bohm's variation of the Einstein-Podolsky-Rosen thought experiment, one can in theory, obtain empirical proof that the photons in Young's double-slit experiment pass through one slit or the other and not through both slits simultaneously, without causing the wavefunction of its coherent superpositioned state vector to collapse. In general, the method of observation employed by the apparatus presented in this paper is different than those used in similar thought experiments [19] [20]. While the implications of this study are immense, the simultaneous observation of light as both wave and particle would fundamentally transform our perception of the wave-particle duality of nature and provide new insight into the completeness of quantum theory as a whole [21].

On the other hand, destruction of the interference pattern on detection screen σ_A caused by the latter observation of where the entangled partner photons land on detection screen σ_B, would strongly suggest that the arrow or passage of time is not absolute. This outcome would represent the fundamental nature of time writ large, meaning the arrow of time is a classical (macroscopic) perception or illusion of how time works. Perhaps the which-path information of the quantum particles passing through the two narrow slits in Young's experiment is causally inaccessible due to the entanglement (or coherent superposition) of space-time at the Planck scale [5] [22]. This idea could provide compelling evidence to support Albert Einstein's provocative assertion regarding the fundamental nature of time [23], which posits that the distinction between the past, present, and future is only a stubbornly persistent illusion.

Data Availability

Data availability is not applicable to this article as no new data was created or analyzed in this study.

Conflicts of Interest

The author declares that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study.

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