A Proposed Double-Slit Experiment Using Momentum-Entangled Photon Pairs

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Introduction: Consider a pair of momentum-entangled photons generated by spontaneous parametric down-conversion (SPDC). This process produces pairs of photons whose momenta are entangled, meaning that the momenta of the two photons are correlated in such a way that measuring the momentum of one photon provides information about the momentum of the other.

State Representation: The two-photon state generated by SPDC can be expressed as:

$$|\Psi\rangle = \int d\vec{k}_1 d\vec{k}_2 f(\vec{k}_1, \vec{k}_2)|\vec{k}_1\rangle_1|\vec{k}_2\rangle_2$$

where $f(\vec{k}_1, \vec{k}_2)$ is the joint amplitude function that encodes the momentum entanglement between the two photons, and $|\vec{k}_i\rangle_i$ represents the state of photon i with momentum $\vec{k}_i$. For entangled photons, $f(\vec{k}_1, \vec{k}_2) \neq f_1(\vec{k}_1)f_2(\vec{k}_2)$, indicating that the momenta of the photons are not independent.

To provide a more precise representation, we can define the joint amplitude function explicitly as:

$$f(\vec{k}_1, \vec{k}_2) = \delta(\vec{k}_1 + \vec{k}_2 - \vec{k}_0)$$

where $\vec{k}_0$ is the initial momentum of the photon pair.

Experimental Setup: The entangled photons are directed to two spatially separated double-slit setups, labeled DS_1 and DS_2. In DS_1 both slits are open, allowing the photon to exhibit wave-like interference. In DS_2, one of the slits is blocked, restricting the photon to a single path and enforcing particle-like behavior.

Wavefunction After the Slits: The wavefunction after the double-slits can be described as:

$$|\Psi'\rangle = \int d\vec{k}_1 d\vec{k}_2 f(\vec{k}_1, \vec{k}_2)[\psi_1(\vec{r}_1) + \psi_2(\vec{r}_1)]\psi_1(\vec{r}_2)|\vec{r}_1\rangle_1|\vec{r}_2\rangle_2$$

where $\psi_i(\vec{r}_j)$ is the wavefunction of a photon passing through slit *i* at position $\vec{r}_j$ on the screen of DS*j*

Probability Distribution Without Which-Way Information: In the absence of any "which-way" measurement, the probability distribution on the screens would be:

$$P(\vec{r}_1, \vec{r}_2) = |\langle \vec{r}_1, \vec{r}_2 | \Psi' \rangle|^2$$

This yields an interference pattern on the screen of DS_1 and a single-slit diffraction pattern on the screen of DS_2.

Impact of Which-Way Measurement: Blocking one slit in DS_2 constitutes a "which-way" measurement. Due to the entanglement, this measurement affects both photons, causing the wavefunction to collapse into a localized particle-like state:

$$|\Psi'' >= \int dk_1 dk_2 f(k_1, k_2) \psi_1(\vec{r_1}) \psi_1(\vec{r_2}) |\vec{r_1} >_1 |\vec{r_2} >_2$$

Consequently, the probability distribution becomes:

$$P'(\vec{r_1}, \vec{r_2}) = |\langle \vec{r_1}, \vec{r_2} | \Psi'' \rangle|^2$$

This results in the disappearance of the interference pattern on the screen of DS_1 , even though no direct measurement was performed on that photon. Both photons exhibit correlated particle-like behavior.

Significance: The experiment demonstrates the non-local effects of quantum entanglement and the complementarity principle. Measuring the "which-way" information of one photon affects its distant entangled partner, causing both to behave like localized particles rather than interfering waves.

Improved Methodology and Considerations

1. Detailed Mathematical Framework: To provide a more precise representation, consider defining the joint amplitude function explicitly as shown above. This ensures a clear mathematical depiction of the entangled state.

2. Enhanced Experimental Setup: Utilize high-efficiency SPDC sources and implement noise reduction techniques to ensure the purity of the entangled state. Advanced techniques such as the use of superconducting nanowire single-photon detectors (SNSPDs) with high temporal resolution can improve the detection of subtle changes in interference patterns.

3. Which-Way Information and Entanglement: Expand the discussion on how which-way information obtained from blocking one slit in DS_2 leads to the collapse of the wavefunction in DS_1. Analyze the mechanism of wavefunction collapse in more detail, illustrating how entanglement ensures that measurement on one photon influences its entangled partner.

4. Simulations and Predictions: Conduct detailed simulations to predict the outcomes of the experiment. Simulations can help identify potential issues and refine the experimental parameters, ensuring a more robust and reliable experimental design.

5. Improved Detection Mechanisms: Employ state-of-the-art single-photon detectors to capture the interference and diffraction patterns with high accuracy. Technologies such as SNSPDs can provide the necessary sensitivity and temporal resolution for this experiment.

Conclusion

The proposed experiment is a compelling approach to investigating quantum entanglement and wave-particle duality. By addressing the detailed mathematical framework, enhancing the experimental setup, and improving detection mechanisms, the design can be refined to produce clearer and more definitive results, contributing to our understanding of fundamental quantum phenomena.

Citations

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