**The Vacuum Fluctuation Pair-Production Model of Single-Photon Double-Slit Interference: The Mechanism of Decoherence Induced by External Field Observation**

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**Abstract:**This paper proposes a novel theoretical model based on the essential nature of the quantum electrodynamics (QED) vacuum, aiming to interpret the phenomenon of single-photon double-slit interference and its decoherence mechanism under the most pristine conditions (without any nonlinear crystals). The core argument is: The observed single-photon interference pattern originates from a high-energy incident photon () exciting, via vacuum quantum fluctuations at a spatial point near the double slit, a virtual electron-positron pair (). This virtual pair annihilates under the boundary conditions provided by the double slit, reconverting into a pair of real low-energy photons (). This photon pair, due to their common spatiotemporal origin, exists in a path-entangled state, and their coincidence counting presents an interference pattern. This paper constructs the effective vertex operator for this process and proves that it satisfies all conservation laws. The key breakthrough is: Any observation attempting to detect “which slit” injects energy into the system, disrupting the delicate balance of the virtual electron-positron pair (), thereby cutting off the production channel of the entangled photon pair and leading to decoherence. This model, for the first time, directly links double-slit interference to the dynamical structure of the vacuum, providing profound insights into the foundations of quantum mechanics rooted in QED.

**Keywords:** Single-photon interference; Quantum electrodynamics (QED); Vacuum fluctuations; Virtual electron-positron pair; Effective vertex; Path entanglement; Decoherence; External field perturbation

1. **Introduction: An Interpretation of Double-Slit Interference Returning to the Essence of the Vacuum**

The single-photon double-slit experiment is a central puzzle of quantum mechanics. Existing theories require the introduction of external media (e.g., nonlinear crystals). This paper aims to explore a more fundamental interpretation: Can interference be explained based solely on the QED vacuum itself? We propose that the root of double-slit interference lies in the fact that the vacuum is not empty but is a dynamic medium filled with virtual particle pairs. Interference results from the interaction between the incident photon and this medium.

1. **Theoretical Framework: The Two-Photon Entanglement Generation Model Based on Vacuum Fluctuations**

**2.1 Physical Picture: The Intermediate Process of the Virtual Electron Pair**

The core physical picture of the model is as follows:  
1. Incidence: A high-energy photon propagates to the vicinity of the double slit.  
2. Fluctuation: Under the condition that the photon energy is sufficiently high (), its electromagnetic field can strongly perturb the vacuum, enabling a virtual electron-positron pair () to “borrow” energy from the vacuum fluctuations and exist for a time allowed by the Heisenberg uncertainty principle.  
3. Annihilation and Production: Under the special boundary conditions provided by the double slit, this virtual pair does not simply annihilate back into the vacuum but undergoes a double-slit-induced coherent annihilation process, transforming into two real photons and , i.e., .  
4. Entanglement: Since and originate from the same spatiotemporal point (vertex) in the same process, their path information is correlated, automatically forming the path-entangled state:

**2.2 Mathematical Formulation: Effective Vertex and Scattering Amplitude**

This process can be described by an effective vertex. Its interaction Lagrangian density is:

where is the effective coupling constant, is the electron field, and are the electromagnetic fields of the pump photon and the two produced photons, respectively.

The scattering amplitude for this process is proportional to:

This amplitude becomes non-zero under the specific momentum transfer provided by the double slit, thereby allowing this process to occur.

1. **The Dynamical Mechanism of Interference and Decoherence**

**3.1 Origin of Interference: Coincidence Counting of Entangled Photons**

The generated entangled two-photon state flies towards the double slit. Its coincidence rate on the screen is:

Fixing the position of one detector and scanning the other yields the standard double-slit interference pattern. This is the true origin of the “single-photon” interference pattern.

**3.2 Mechanism of Decoherence: External Energy Injection and Suppression of the Virtual Process**

The essence of decoherence is: Any device attempting to observe the particle path necessarily injects energy into the system.

1. Decoherence Factor: The injection of external field energy disrupts the brief energy-time uncertainty relation upon which the existence of the virtual electron pair depends. This is equivalent to introducing a decoherence suppression factor into the scattering amplitude:

where is the characteristic existence time of the virtual electron pair. When is sufficiently large,

1. Post-Decoherence Picture: When the effective vertex process is completely suppressed. The incident photon can only pass through the double slit in a classical manner, and its probability distribution becomes:

The interference pattern completely disappears.

**4. Conclusion**

This paper proposes a single-photon double-slit interference model based on QED vacuum fluctuations, drawing the following conclusions:

1. New Interference Mechanism: The “single-photon” interference pattern实质上 (essentially) stems from the coincidence measurement of entangled photon pairs produced by high-energy photons exciting the vacuum, not from the same photon simultaneously passing through both slits.
2. New Interpretation of Decoherence: “Wavefunction collapse” dynamically originates from the suppression of the virtual processes in the vacuum by energy injection from external field observation, which severs the production channel of the entangled pair.
3. Theoretical Self-Consistency: The model strictly adheres to energy, momentum, and charge conservation laws, and defines the role of the double slit as providing the specific boundary conditions required for coherent annihilation.
4. Philosophical Breakthrough: The model successfully attributes the mystery of quantum phenomena from the vagueness of “wave-particle duality” to the dynamical attributes of the QED vacuum, providing a more solid physical foundation for understanding quantum reality.

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