**The Vacuum Bremsstrahlung Model of Single-Electron Double-Slit Interference: The Suppression of Quantum Fluctuations and Decoherence Mechanism by External Field Observation**

**Authors:** Li Zhijun, Zhao Guangyao

**Abstract:**  
This paper proposes a complete theoretical model based on quantum electrodynamics (QED) to uniformly interpret the phenomenon of single-electron double-slit interference and its decoherence under observation. The core argument is: The observed electron interference pattern originates from a high-energy incident electron () undergoing bremsstrahlung via vacuum quantum fluctuations in the Coulomb field of an atomic nucleus at the edge of the double slit, producing a low-energy electron () and a photon (); the three particles are in a quantum entangled state due to their common spatiotemporal vertex. The joint detection of this entangled state presents an interference pattern. Starting from the Feynman rules of QED, this paper derives the scattering amplitude for this process, proving that it satisfies all conservation laws. The key breakthrough is: Any observation attempting to detect “which slit” injects energy into the system. This external field disrupts the subtle energy-time uncertainty relation required to maintain vacuum quantum fluctuations, thereby effectively suppressing the bremsstrahlung process, cutting off the generation channel of the entangled state, and leading to decoherence. The model introduces an external field suppression factor quantitatively describing the continuous transition from perfect interference to complete decoherence, providing a unified interpretation for the foundational problems of quantum mechanics that combines mathematical rigor with physical depth.

**Keywords:** Single-electron interference; Quantum electrodynamics (QED); Bremsstrahlung; Vacuum fluctuations; Quantum entanglement; External field observation; Decoherence; Suppression factor

1. **Introduction: From Path Superposition to Vacuum Excitation and Decoherence**

The single-electron double-slit experiment is a central puzzle of quantum mechanics. This paper aims to explore an interpretation based on the essence of the QED vacuum: The root of electron interference lies in the interaction between high-energy electrons and vacuum fluctuations, while decoherence stems from the suppression of this interaction by external field observation. We propose that interference does not arise from an electron simultaneously passing through both slits, but rather from the electron generating an entangled pair via bremsstrahlung excitation at the slit edge; any observation disrupts this excitation process.

1. **Theoretical Framework: Bremsstrahlung and Entanglement Generation in the QED Vacuum**

**2.1 Physical Picture: Vacuum Fluctuations as an Intermediate Medium**

The core physical process of the model is as follows:  
1. Incidence: A high-energy electron propagates to the vicinity of an atomic nucleus () at the edge of the double slit.  
2. Fluctuation and Radiation: In the Coulomb field of the atomic nucleus, the electron’s state of motion changes急剧ly (acceleration/deceleration). This change strongly perturbs the vacuum and, through interaction with the vacuum’s virtual photon field, results in bremsstrahlung, radiating a real photon ().  
3. Energy Conservation and Entanglement Generation: The energy of the radiated photon comes from the kinetic energy of the incident electron. The process can be represented as: Since the final-state electron and photon originate from the same vertex, their wave functions automatically enter a quantum entangled state.

**2.2 Mathematical Formulation: QED Scattering Amplitude**

This process is precisely described by the Feynman rules of QED. Its scattering amplitude is:

where is the three-dimensional momentum transferred by the atomic nucleus. This amplitude strictly satisfies energy, momentum, and charge conservation laws. From this, the radiation probability can be calculated.

**2.3 Establishment of the Entangled State**

After radiation, the system evolves into an electron-photon entangled state:

This entangled state is the physical origin of the subsequent double-slit interference phenomenon.

1. **The Complete Dynamics of Interference and Decoherence**

**3.1 Origin of Interference: Coincidence Detection of the Entangled State**

The entangled pair flies towards the double slit. Its joint detection probability (coincidence rate) on the screen presents an interference pattern:

Fixing the photon detector position and scanning the electron detector will yield the electron double-slit interference pattern.

**3.2 Mechanism of Decoherence: Suppression of Vacuum Fluctuations by an External Field**

Any observation attempting to detect the electron’s path inherently injects energy into the system. This has a fatal impact on the QED vacuum fluctuation process:

1. Decoherence Suppression Factor: Vacuum quantum fluctuations (the generation and annihilation of virtual particle pairs) rely on the Heisenberg uncertainty principle The injection of external field energy is equivalent to imposing a measurement with an energy precision of which directly destroys the energy uncertainty essential for the virtual process. Its effect can be quantitatively described by a decoherence suppression factor:

where is the characteristic time of the bremsstrahlung process (i.e., the characteristic existence time of the virtual photon). When

1. Post-Decoherence Picture: After the external field is injected, the effective radiation probability is suppressed to:

When the bremsstrahlung process is completely shut down. The incident electron can no longer generate entangled photon pairs and can only pass through the double slit as a classical particle. Its probability distribution becomes:

The interference pattern completely disappears.

1. **Conclusion**

This paper establishes a vacuum bremsstrahlung model for single-electron double-slit interference and reveals the microscopic mechanism of decoherence caused by external field observation, drawing the following conclusions:

1. New Interference Mechanism: The electron interference pattern originates from the coincidence measurement of electron-photon entangled pairs produced by bremsstrahlung, not from a single electron simultaneously passing through both slits.
2. New Decoherence Mechanism: “Wave function collapse” dynamically stems from external energy injection suppressing the quantum fluctuations of the QED vacuum, cutting off the source of entangled pair generation.
3. Mathematical Self-Consistency: The model is entirely built within the strict framework of QED and introduces a calculable decoherence suppression factor achieving a continuous transition description from quantum to classical.
4. Unity and Profundity: This model unifies quantum phenomena and their disappearance into the dynamic properties of the QED vacuum, providing a more solid and profound physical basis for understanding quantum mechanics.

**References**[1] Li, Z.J., Zhao, G.Y. “The ABC Mechanism in the Cosmos”. Preprint (2023).  
[2] Berestetskii, V.B., et al. Quantum Electrodynamics. Pergamon Press (1982). [QED and Bremsstrahlung]  
[3] Heisenberg, W. The Physical Principles of the Quantum Theory. (1930). [Uncertainty Principle]  
[4] Zurek, W.H. “Decoherence and the transition from quantum to classical”. Physics Today (1991). [Decoherence Theory]