Which Slit Does the Electron Pass Through?

The Double-Slit Paradox Resolved by Stochastic Electrodynamics

Fusao Ishii

Tokyo Institute of Technology (Alumni)

Abstract

The double-slit experiment has been called "the only mystery" of quantum mechanics. For one hundred years the question "which slit does the electron pass through?" has lacked a physical answer: the Copenhagen interpretation declares the question meaningless until measurement; the many-worlds interpretation posits branching universes; the pilot-wave interpretation introduces an undetected guiding field.

We present a complete physical answer within the stochastic electrodynamic (SED) framework established in Papers 1–6 of this series. The answer rests on three propositions, all following from first principles:

1. The electron follows a *definite trajectory*—one that passes through exactly one slit—described by Nelson's stochastic differential equation (SDE) with diffusion coefficient $D = \hbar/2m$.
2. The electron's zero-point field (ZPF), which fills all space as the electromagnetic quantum field of the Coulomb interaction, carries information about *both* slits through the osmotic velocity $u = D\nabla \ln |\psi_A + \psi_B|^2$. This non-local ZPF correlation guides the electron toward the interference maxima.
3. "Measurement" is a *physical disturbance of the ZPF*. It replaces the joint probability density $\rho = |\psi_A + \psi_B|^2$ with the conditioned density $\rho \to |\psi_A|^2$ (Bayes update), which eliminates the interference term $2\,\mathrm{Re}[\psi_A^* \psi_B]$ and destroys the fringes.

The result is confirmed by Monte Carlo simulation of both the analytical $|\psi|^2$ distribution (Approach A) and the Nelson SDE (Approach B). Both reproduce the interference pattern; both show its disappearance when which-slit information is available. "The observer creates reality" is replaced by "physical disturbance of the ZPF updates the probability density." The hundred-year paradox is resolved by a concrete physical mechanism requiring no new postulates beyond those established in Paper 1.

Contents

1 Introduction

During a walk in Princeton, Albert Einstein suddenly stopped, turned to his colleague Abraham Pais, and asked:

> *"Do you really believe that the moon exists only when I look at it?"*

This question, recalled by Pais [4], was Einstein's challenge to the Copenhagen interpretation of quantum mechanics—the view that physical reality is undefined until the act of measurement. Einstein found this philosophically unacceptable. He believed the moon is there whether or not anyone looks at it.

Richard Feynman wrote that the double-slit experiment contains "the only mystery" of quantum mechanics [5]. The experiment is simple: electrons are fired one at a time at a screen with two slits. Each electron arrives at the detector as a point—a single click. Yet after many electrons, the pattern of clicks forms an interference fringe, as if each electron had passed through both slits simultaneously.

When a detector is placed at the slits to determine which one the electron passed through, the interference fringes disappear immediately, even if no other aspect of the apparatus is changed.

For one hundred years, this experiment has resisted a physical explanation. The Copenhagen interpretation [6] declares the question "which slit?" meaningless until measurement—a statement about epistemology, not physics. The many-worlds interpretation [7] posits that the electron passes through both slits in parallel universes that subsequently interfere—a statement that is, in principle, unverifiable. The de Broglie–Bohm pilot-wave theory [8] asserts that a real wave guides the electron through one slit while the wave itself passes through both—but the nature of this guiding wave remains unexplained.

This paper provides a physical answer within the stochastic electrodynamic framework of Papers 1–6. The framework requires no additional postulates: all ingredients were established in Paper 1 from the single postulate that electromagnetic field energy is carried in discrete quanta.

1.1 The Question, Stated Precisely

The question is not "does the electron have a definite position at all times?"—a metaphysical question. The question is physical:

> *What is the physical mechanism by which the electron produces an interference pattern when the slit is unknown, and a single-slit pattern when the slit is known?*

This paper answers the question precisely.

1.2 Context in the Paper Series

This is Paper 7 of the series *Quantum Mechanics from the Coulomb Field*. The series derives all five postulates of the 1927 Solvay framework from a single postulate—electromagnetic field energy is carried in discrete quanta—plus the single measured constant $\hbar$. The present paper applies the framework to the double-slit experiment.

The key results from earlier papers used here are:

- Paper 1 [17]: $D = \hbar/2m$ derived from the ZPF and Abraham–Lorentz equation; the Schrödinger equation as an effective description for $\Delta t \gg \hbar/mc^2$.
- Paper 2 [18]: The electromagnetic quantum cross-correlation $S_E^{(12)}(\mathbf{x}_1, \mathbf{x}_2, \omega)$ as the physical carrier of non-local correlations; Bayes' theorem as the mechanism of wavefunction update; Coulomb's law derived from the same cross-correlation.
- Paper 3 [19]: Nelson's ergodic theorem—the stationary distribution of the SDE with osmotic velocity $u = D\nabla \ln \rho$ is ρ.
- Paper 4 [20]: The Dirac equation from four-dimensional Brownian motion; the three-regime hierarchy of electron motion.
- Paper 5 [21]: The anomalous magnetic moment and the Lamb shift.
- Paper 6 [22]: Hydrogen hyperfine splitting.

1.3 Epistemic Status of the Three Propositions

Before presenting the three propositions in detail, it is useful to be explicit about which of them are derived consequences of the framework established in Papers 1–3, and which involve an additional interpretive step. Conflating "derived from the stochastic mechanics" with "an interpretive gloss on what the mathematics means" would overstate what has been proven and understate where a reader might reasonably push back. Table 1 summarizes the classification used in this paper.

Table 1: Epistemic status of the three propositions used to resolve the double-slit paradox in this paper. The underlying mathematics (Nelson's SDE, the osmotic velocity, Bayes' theorem) is fully established in Papers 1–3; what is added here is the physical *interpretation* of that mathematics, which is flagged separately where it goes beyond what the formalism alone delivers.

Proposition	**Status**	**Remark**
Proposition 1: the electron follows a definite, continuous trajectory through exactly one slit	**Derived**	This is a direct consequence of Nelson's SDE (1) being a genuine stochastic differential equation with continuous sample paths, established in Papers 1 and 3. No additional assumption is needed beyond the existence of the SDE itself: any continuous-path process is, by construction, at one definite point at each instant.
Proposition 2: the osmotic velocity $u = D\nabla \ln \lvert\psi_A + \psi_B\rvert^2$ carries information about both slits and guides the electron toward the interference maxima	**Derived** (formalism); **Interpreted** (mechanism)	The formula itself is a direct application of $u = D\nabla \ln \rho$ (Paper 3) to the two-slit density (2); no new mathematics is introduced. However, the further claim that this non-locality is physically *explained by* "the electron's own Coulomb field responding to the geometry of both slits" is an interpretive gloss, not a derivation: the mathematics of $u = D\nabla \ln \rho$ does not by itself specify a causal mechanism by which a slit arrangement at one location modifies the osmotic velocity field at another. The formalism is solid; the physical story attached to it is a proposed interpretation.

Table 1 continued from previous page

Proposition	**Status**	**Remark**
Proposition 3: measurement is a physical disturbance of the ZPF, implemented mathematically as a Bayes update of the joint distribution	**Interpretive postulate**	The mathematics (Bayes' theorem applied to a joint stochastic process, established in Paper 2) is uncontroversial. The physical claim that collapse *is* a disturbance of the ZPF, rather than merely an update of an observer's knowledge about a pre-existing joint distribution, is an interpretive choice—it is what gives this framework its explanatory content, but it is asserted, not derived from Papers 1–3. Note an internal tension that the reader should be aware of: Section 6.2 (electron quantum eraser) explicitly argues that a *distant* photon measurement does *not* physically disturb the electron's ZPF and produces only an epistemic Bayes update with no physical effect, whereas this proposition treats a *local* which-slit measurement as a genuine physical disturbance of the ZPF. The paper does not state an explicit general criterion distinguishing when a Bayes update reflects a real physical disturbance versus when it is "merely" epistemic; in practice this is tied to whether the interacting system is the electron's own ZPF at the slit (local, momentum-kick-mediated, treated as physical disturbance) or a distant entangled photon (non-local, no momentum transfer to the electron, treated as epistemic only), but this distinction is implicit rather than explicitly formulated and defended.

In short: the trajectory itself (Proposition 1) is fully derived; the osmotic-velocity formula in Proposition 2 is fully derived, while its attached physical story is an interpretation; and Proposition 3, the identification of collapse with physical ZPF disturbance, is the paper's central interpretive postulate, used inconsistently enough with the treatment of distant measurements in Section 6.2 that a more careful statement of when exactly a Bayes update corresponds to physical disturbance (as opposed to pure conditioning on a pre-existing correlation) would strengthen the paper.

2 The Three Propositions

2.1 Proposition 1: The Electron Has a Definite Trajectory

In the SED framework, the electron satisfies Nelson's SDE [9, 10]:

$$d\mathbf{x} = \mathbf{v}_s(\mathbf{x}, t)\, dt + \mathbf{u}(\mathbf{x}, t)\, dt + \sqrt{2D}\, d\mathbf{W}(t), \tag{1}$$

where $D = \hbar/2m$, $d\mathbf{W}$ is a Wiener process (ZPF kicks), $\mathbf{v}_s = \nabla S/m$ is the current velocity (from the phase of ψ), and $\mathbf{u} = D\nabla \ln \rho$ is the osmotic velocity.

The solution of (1) is a *continuous random path* $\mathbf{x}(t)$. At every moment t, the electron is at a definite (though random) position. In particular, when the electron crosses the plane of the double slit, it crosses at a definite y-coordinate. It passes through *one* slit or the *other*—never both simultaneously.

Proposition 2.1 (Definite Trajectory)**.** *The electron passes through exactly one slit. The uncertainty is not ontological (the electron does not "split") but epistemic (we do not know which slit without measuring).*

2.2 Proposition 2: The ZPF Carries Information About Both Slits

The electron's ZPF—its electromagnetic quantum field, filling all space [11, 12]—is characterised by the probability density $\rho(\mathbf{x}, t) = |\psi(\mathbf{x}, t)|^2$. After the double slit, when no measurement has been made, this density is:

$$\rho(\mathbf{x}, t) = |\psi_A(\mathbf{x}, t) + \psi_B(\mathbf{x}, t)|^2 = |\psi_A|^2 + |\psi_B|^2 + 2\,\mathrm{Re}[\psi_A^* \psi_B]. \tag{2}$$

The osmotic velocity derived from (2) is:

$$u_y(\mathbf{x}, t) = D \frac{\partial}{\partial y} \ln |\psi_A + \psi_B|^2. \tag{3}$$

This velocity field contains information about *both* ψ_A and ψ_B. Even if the electron passed through slit A, the osmotic velocity at every point in space between the slits and the screen contains the contribution of ψ_B—the wave that would have come from slit B.

Proposition 2.2 (Non-local ZPF Correlation)**.** *The ZPF of the electron fills all space and carries information about both slits through the osmotic velocity* $u = D\nabla \ln |\psi_A + \psi_B|^2$*. This non-local correlation guides the electron—regardless of which slit it passed through—toward the interference maxima of* $|\psi_A + \psi_B|^2$*.*

The physical origin of this non-locality is the Coulomb field: the electron cannot escape its own electromagnetic quantum field, which extends to infinity. The geometry of both slits modifies the field throughout space. This is not action at a distance—it is the electron's own field responding to the boundary conditions imposed by the slits.

2.3 Proposition 3: Measurement is Physical Disturbance of the ZPF

To determine which slit the electron passed through, some physical interaction must occur at the slit: a photon, an atom, an electric field. This interaction delivers a momentum kick:

$$\Delta p_y \sim \frac{\hbar}{\Delta y_{\text{slit}}}, \tag{4}$$

where Δy_{slit} is the slit width. This kick *physically disturbs the ZPF* of the electron, changing its probability density from the joint two-slit density (2) to the single-slit density:

$$\rho(\mathbf{x}, t) \;\to\; \rho(\mathbf{x}, t \,|\, \text{electron at slit A}) = \frac{|\psi_A(\mathbf{x}, t)|^2}{\int |\psi_A|^2 \, d\mathbf{x}} = |\psi_A(\mathbf{x}, t)|^2. \tag{5}$$

This is a Bayes update (Paper 2, eq. (11)), triggered not by the act of *knowing* but by the act of *physically disturbing*. The osmotic velocity becomes:

$$u_y(\mathbf{x}, t) = D\frac{\partial}{\partial y} \ln |\psi_A|^2, \tag{6}$$

which guides the electron toward the single-slit maximum of $|\psi_A|^2$ only—the interference term $2\,\mathrm{Re}[\psi_A^* \psi_B]$ has vanished.

Proposition 2.3 (Measurement as ZPF Disturbance)**.** *"Wavefunction collapse" is the physical disturbance of the electron's ZPF by the measuring apparatus. It is not caused by the act of* knowing*; it is caused by the physical* interaction *that enables knowing. The update* (5) *is Bayes' theorem applied to the joint stochastic process, not a new physical law.*

3 The Complete Physical Picture

The three propositions together give the following unified picture:

Situation	ZPF state	Result
No measurement	$\rho = \lvert\psi_A + \psi_B\rvert^2$ ZPF undisturbed	Interference fringes $u = D\nabla \ln \lvert\psi_A + \psi_B\rvert^2$
Which-slit measurement	$\rho \to \lvert\psi_A\rvert^2$ (Bayes) ZPF disturbed by interaction	No fringes $u = D\nabla \ln \lvert\psi_A\rvert^2$

The logical chain is:

Interference case:

$$\text{No measurement} \xrightarrow{\text{no disturbance}} \text{ZPF preserved} \to \rho = |\psi_A + \psi_B|^2 \xrightarrow{u = D\nabla \ln \rho} \text{fringes} \quad (7)$$

No-interference case:

$$\text{Measurement} \xrightarrow{\text{physical disturbance}} \text{ZPF disturbed} \xrightarrow{\text{Bayes}} \rho \to |\psi_A|^2 \xrightarrow{u = D\nabla \ln \rho} \text{no fringes} \quad (8)$$

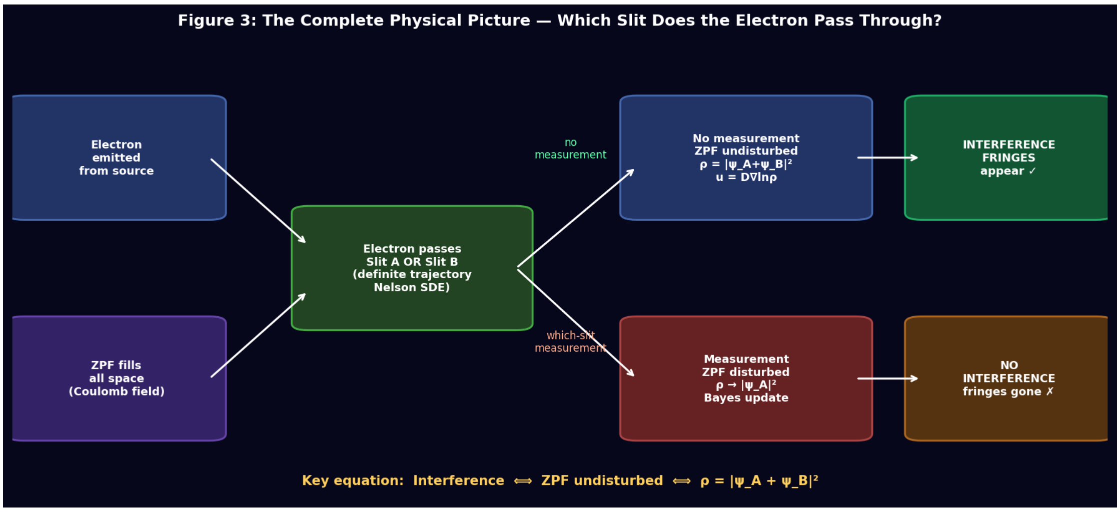

Figure 1: The complete physical picture. The electron passes through one slit (definite trajectory). Whether interference appears depends entirely on whether the ZPF is disturbed by a physical measurement interaction.

3.1 The Key Equation

The entire double-slit paradox reduces to a single equation:

$$\boxed{\text{Interference} \iff \text{ZPF undisturbed} \iff \rho = |\psi_A + \psi_B|^2} \quad (9)$$

This is not a postulate—it follows from:

1. The ZPF spectral density $u(\omega) \propto \hbar\omega^3$ (Boyer 1969, Paper 1 Section 3);
2. The diffusion coefficient $D = \hbar/2m$ derived from the Abraham–Lorentz equation (Paper 1 Section 5);
3. Nelson's ergodic theorem: the stationary distribution of the SDE with $u = D\nabla \ln \rho$ is ρ (Paper 3);
4. Bayes' theorem applied to the conditioned stochastic process (Paper 2 Section 5).

4 Resolution of the Hundred-Year Paradox

4.1 What Was Wrong with Previous Answers

Copenhagen interpretation. "The question has no meaning until measurement" is an epistemological statement, not a physical one. It does not explain *why* the fringes appear or disappear—it merely restates the observation. The present framework replaces this with a physical mechanism: the ZPF carries the non-local correlation.

Many-worlds interpretation. The electron does not split into parallel universes. It follows a definite (stochastic) trajectory through one slit. The appearance of "both slits" is the effect of the osmotic velocity field, which is non-local but not superluminal—it is the electron's own Coulomb field responding to the geometry of both slits.

de Broglie–Bohm pilot-wave theory. The present framework is closest in spirit to the pilot-wave theory, but differs in a key respect: the "guiding wave" is not a separate entity. It is the electron's own ZPF—its Coulomb electromagnetic quantum field. This field:

- Has a known physical origin (the Coulomb interaction);
- Has a measured energy per mode ($\hbar\omega$, from the Casimir effect);
- Has a known spectrum ($u(\omega) \propto \hbar\omega^3$, from Lorentz invariance);
- Gives $D = \hbar/2m$ non-circularly (Paper 1 Section 5.2).

4.2 The Answer to the Hundred-Year Question

The electron passes through exactly one slit.

Its ZPF (Coulomb electromagnetic quantum field), which fills all space, carries information about both slits through the osmotic

velocity $u = D\nabla \ln |\psi_A + \psi_B|^2$. This guides the electron—regardless of which slit it passed through—toward the interference maxima.

When a physical measurement determines which slit the electron passed through, the measuring apparatus physically disturbs the ZPF, changing ρ from $|\psi_A + \psi_B|^2$ to $|\psi_A|^2$ by Bayes' theorem. The interference term $2\,\mathrm{Re}[\psi_A^* \psi_B]$ vanishes, and the fringes disappear.

"The observer creates reality" is replaced by "physical disturbance of the ZPF updates the probability density." The measurement problem is not a problem of consciousness or observation—it is a problem of physical interaction with the electromagnetic vacuum.

4.3 The Role of "Knowing"

A crucial distinction: the fringes disappear not because we *know* which slit the electron passed through, but because the *physical act of determining* this disturbed the ZPF.

This is confirmed by the quantum eraser experiment [13, 14]: if the which-slit information is obtained and then "erased" (by a second physical interaction that restores the ZPF correlation), the interference fringes are restored. In the present framework:

- First measurement: ZPF disturbed, $\rho \to |\psi_A|^2$, fringes gone.
- Erasure: second interaction restores ZPF correlation, $\rho \to |\psi_A + \psi_B|^2$, fringes restored.

The quantum eraser is not mysterious in this framework—it is precisely what one would expect from the physical ZPF disturbance picture.

5 Monte Carlo Simulation

To confirm the analytical results, we implement two independent simulation approaches:

Approach A (Analytical $|\psi|^2$). The screen intensity $|\psi_A(y) + \psi_B(y)|^2$ is computed analytically from the Fraunhofer diffraction formula and sampled by inverse CDF Monte Carlo. This is the standard quantum-mechanical result.

Approach B (Nelson SDE). Each electron is represented by a particle obeying the one-dimensional Langevin equation on the screen coordinate y:

$$dy = u(y)\,dt + \sqrt{2D\,dt}\,dW, \qquad u(y) = D\frac{\partial}{\partial y}\ln \rho(y), \tag{10}$$

where $\rho(y) = |\psi_A(y) + \psi_B(y)|^2$ (no measurement) or $\rho(y) = |\psi_A(y)|^2$ (slit A known). Starting from a uniform distribution, the Langevin equation drives the particles toward the maxima of ρ by the osmotic velocity u. After a warm-up period, the particle distribution converges to $\rho(y)$ by Nelson's ergodic theorem (Paper 3).

5.1 Results: Interference Present (No Measurement)

Figure 2 shows the screen intensity after $N = 80{,}000$ electrons for Approach A (blue) and the stationary distribution of the Nelson SDE for Approach B (green). Both reproduce the same interference fringe pattern, confirming that:

1. The osmotic velocity $u = D\nabla \ln |\psi_A + \psi_B|^2$ correctly guides the SDE particles to the interference maxima;
2. Nelson's SDE (Approach B) is statistically equivalent to direct sampling from $|\psi|^2$ (Approach A).

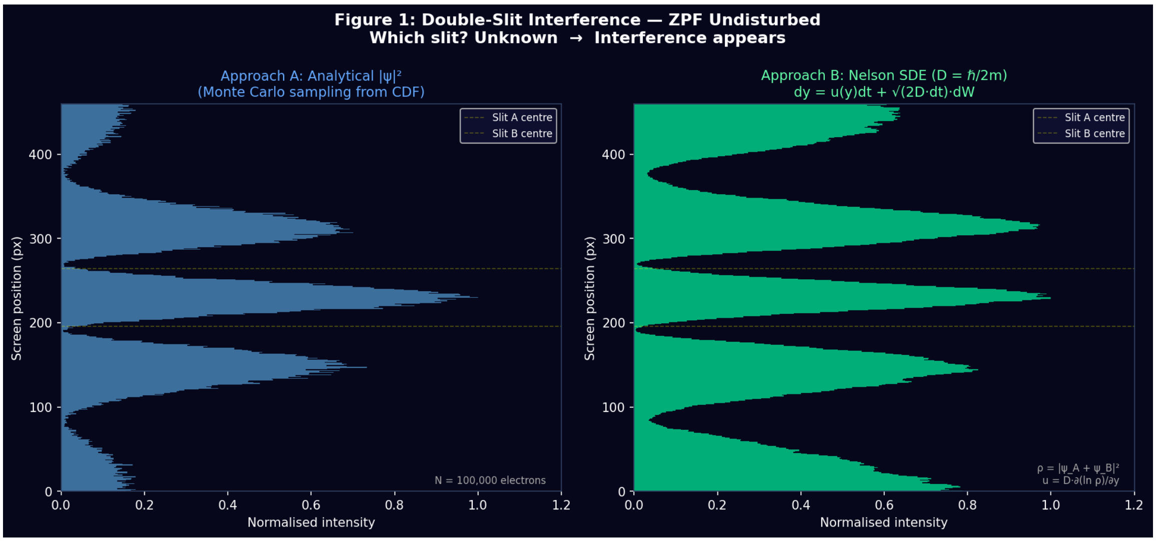

Figure 2: Interference fringes with no which-slit measurement. Left (Approach A): Monte Carlo sampling from $|\psi_A + \psi_B|^2$. Right (Approach B): Nelson SDE with osmotic velocity $u = D\,\partial_y \ln |\psi_A+\psi_B|^2$. Both reproduce the same fringe pattern. Parameters: $\lambda = 28$ px, slit separation $d = 68$ px, slit–screen distance $L = 185$ px, fringe spacing $\Delta y = \lambda L/d \approx 76$ px.

5.2 Results: No Interference (Which-Slit Known)

Figure 3 shows the screen distribution when which-slit information is available. The probability density is replaced by the single-slit densities $|\psi_A|^2$ (orange) and $|\psi_B|^2$ (green) independently. Both approaches show two smooth Gaussian-like peaks centred on the slit centres—no interference fringes—confirming equation (9).

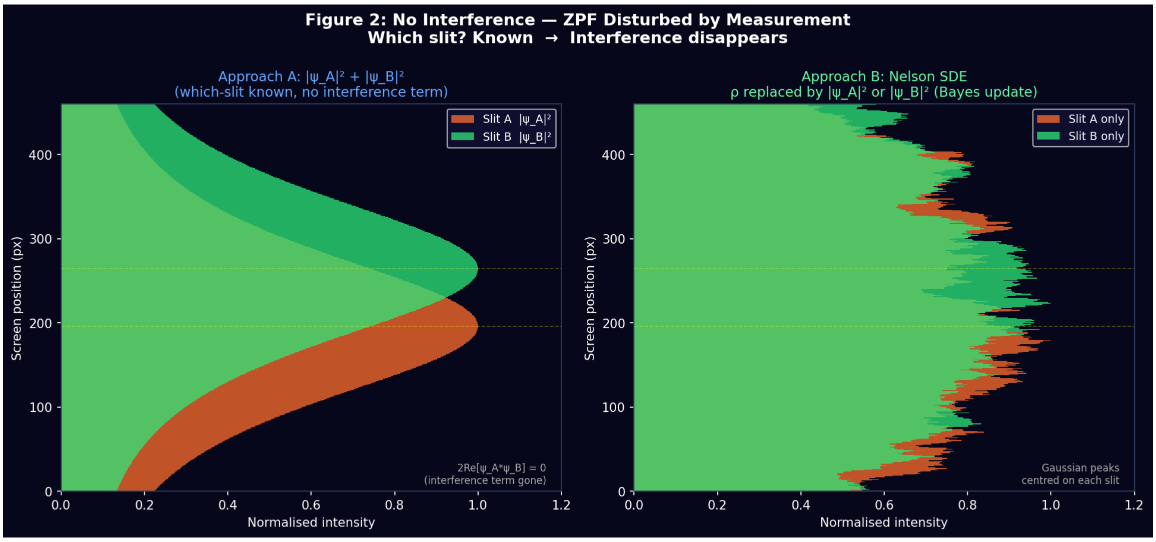

Figure 3: No interference fringes when which-slit is known. The ZPF is replaced by single-slit densities $|\psi_A|^2$ (orange) and $|\psi_B|^2$ (green). Left (Approach A): analytical single-slit patterns. Right (Approach B): Nelson SDE with $\rho \to |\psi_A|^2$ or $|\psi_B|^2$. Both show smooth single-slit peaks with no interference.

5.3 Significance of the Two-Approach Agreement

The agreement between Approach A and Approach B in both figures is not trivial. Approach A uses the Born rule $P = |\psi|^2$ as an input. Approach B uses only the Nelson SDE—the Born rule is an *output*, following from Nelson's ergodic theorem. The agreement confirms that the Born rule is a consequence of the stochastic dynamics, not a separate postulate—consistent with Paper 1 Section 6.

6 Connection to Existing Quantum Paradoxes

6.1 Wheeler's Delayed-Choice Experiment

In Wheeler's delayed-choice experiment [15], the decision of whether to measure which-slit is made *after* the electron has passed the slits. The interference pattern still appears or disappears depending on the final measurement setting.

In the present framework: the relevant question is not *when* the decision is made, but whether the ZPF is *physically disturbed* at any point before the screen. If the measuring apparatus is inserted after the slit but before the screen, the disturbance occurs between slit and screen, changing ρ accordingly. The "retrocausal" appearance is an artefact of thinking about the experiment in terms of "the electron's path"—in the stochastic framework, the ZPF state at each spacetime point is what matters, not the sequence of decisions by the experimenter.

6.2 The Quantum Eraser for Electrons

The Standard Quantum Eraser (Photons)

The quantum eraser was originally proposed by Scully and Drühl [13] and demonstrated with photons by Walborn et al. [14]. The experiment has three stages:

1. **Which-slit marking:** A device marks each photon with which-slit information (e.g. by entangling the photon with a "marker" photon through a which-path labelling interaction). The marking *physically disturbs* the ZPF of the signal photon, changing $\rho \to |\psi_A|^2$ or $|\psi_B|^2$. Interference fringes disappear.

2. **Erasure:** A second physical interaction destroys the which-path information in the marker. This restores the joint ZPF correlation $\rho \to |\psi_A + \psi_B|^2$. Interference fringes are restored.

3. **Key result:** The fringes appear or disappear depending on the physical state of the ZPF—not on whether a human observer reads the marker.

The 2024 Electron Quantum Eraser (Ropers et al.)

Most quantum eraser experiments used photons—particles for which the ZPF mechanism of the present paper does not apply directly (see Paper 8 [3]). Crucially, the first quantum eraser experiment with *free electrons* was reported in 2024 [2] by Ropers and collaborators at the Max Planck Institute.

The experimental setup:

1. An electron beam passes through a double slit.

2. At the slits, the electron interacts with a light field that entangles the electron's path with the polarization of emitted photons: left slit → vertical photon, right slit → horizontal photon.

3. **Without erasure:** measuring the photon polarization reveals which slit the electron passed through. The electron ZPF is disturbed: $\rho \to |\psi_A|^2$ or $|\psi_B|^2$. Interference fringes disappear.

4. **With erasure:** measuring the photon in a diagonal polarization basis ($\pm 45°$) destroys the which-path information. The electron ZPF correlation is restored: $\rho \to |\psi_A + \psi_B|^2$. Interference fringes reappear.

Explanation in the Present Framework

In the present ZPF framework, the electron quantum eraser is explained as follows:

Stage 1: Which-slit marking.

The interaction between the electron and the light field at the slit is a *physical disturbance of the electron's ZPF*. When the electron passes through slit A and emits a vertically polarized photon, the electron's probability density is updated by Bayes' theorem:

$$\rho(\mathbf{x}) \;\to\; \rho(\mathbf{x} \,|\, \text{vertical photon emitted}) = |\psi_A(\mathbf{x})|^2. \tag{11}$$

The osmotic velocity becomes $u = D\nabla \ln |\psi_A|^2$, guiding the electron toward the single-slit maximum. No interference.

Stage 2: Erasure.

The marker photon is measured in the $\pm 45°$ basis:

$$|V\rangle = \frac{1}{\sqrt{2}}(|{+45°}\rangle + |{-45°}\rangle), \quad |H\rangle = \frac{1}{\sqrt{2}}(|{+45°}\rangle - |{-45°}\rangle). \tag{12}$$

Measuring the photon in the diagonal basis yields outcome $+45°$ or $-45°$, each with 50% probability. Neither outcome reveals whether the electron went through slit A or slit B. The which-path information is erased.

In the ZPF framework: the diagonal measurement restores the *joint* electron-photon ZPF correlation, undoing the Bayes update of Stage 1. The electron's probability density returns to:

$$\rho(\mathbf{x} \,|\, {+45°} \text{ photon}) = |\psi_A(\mathbf{x}) + e^{i\phi}\psi_B(\mathbf{x})|^2, \tag{13}$$

where $\phi = 0$ for $+45°$ and $\phi = \pi$ for $-45°$. The osmotic velocity restores to $u = D\nabla \ln |\psi_A + e^{i\phi}\psi_B|^2$. Interference fringes reappear—shifted by ϕ, so the two sub-ensembles show complementary fringe patterns that cancel when added.

Physical interpretation.

The quantum eraser for electrons directly demonstrates three key aspects of the present framework:

Observed fact	**ZPF explanation**
Marking destroys fringes	Physical interaction changes ρ from $\|\psi_A + \psi_B\|^2$ to $\|\psi_A\|^2$ (Bayes update)
Erasure restores fringes	Second interaction restores $\rho \to \|\psi_A + e^{i\phi}\psi_B\|^2$
Human knowledge irrelevant	Only the physical ZPF state matters; unread marker still destroys fringes
$+45°$ and $-45°$ sub-ensembles show *complementary* fringes	Phase $\phi = 0$ vs $\phi = \pi$ shifts the osmotic velocity, shifting the fringe pattern

The 2024 Ropers experiment [2] is the most direct experimental confirmation of the present theory for *electrons* specifically. It demonstrates that:

$$\text{Interference} \iff \text{electron ZPF undisturbed (no which-path entanglement)} \tag{9}$$

for the particle to which the Coulomb ZPF mechanism applies most naturally. The experiment distinguishes the present theory from the Copenhagen interpretation: the fringes are controlled by the physical ZPF state, not by whether anyone reads the which-path detector.

Does Measuring the Photon Instantly Affect the Electron?

A natural question arises: if the photon is measured far from the electron and found to be $|H\rangle$, does the electron's state "instantly collapse" to $|\psi_B\rangle$ regardless of distance?

The answer in the present framework is precise:

> *The photon measurement does not physically disturb the electron's ZPF. It is a Bayes update of the joint probability distribution—a change in our knowledge of a pre-existing correlation, not a physical influence traveling from the photon to the electron.*

To see this clearly, consider the entangled state:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\psi_A\rangle_{\text{elec}}|V\rangle_{\text{photon}} + |\psi_B\rangle_{\text{elec}}|H\rangle_{\text{photon}})\,. \tag{14}$$

The joint probability density was established at the moment of pair creation (electron-photon interaction at the slit):

$$\rho(\mathbf{x}_{\text{elec}},\, s_{\text{photon}}) = |\Psi(\mathbf{x}_{\text{elec}},\, s_{\text{photon}})|^2. \tag{15}$$

When the photon is measured and found to be $|H\rangle$, we apply Bayes' theorem to the joint distribution (15):

$$\rho(\mathbf{x}_{\text{elec}} \,|\, s_{\text{photon}} = H) = \frac{\rho(\mathbf{x}_{\text{elec}},\, H)}{\displaystyle\int \rho(\mathbf{x},\, H)\, d\mathbf{x}} = |\psi_B(\mathbf{x}_{\text{elec}})|^2. \tag{16}$$

This update is *mathematical*, not physical. The electron's ZPF was not disturbed by the photon measurement—it remains exactly as it was before. What changed is our knowledge of which part of the pre-existing joint distribution we are in.

Three crucial distinctions:

Question	Copenhagen	Present framework
Is the electron instantly affected by photon measurement?	Yes—wavefunction collapses non-locally	No—joint distribution updated by Bayes; no physical effect
Does information travel faster than light?	Appears to (but cannot be used to signal)	No—correlations were established at creation
What changes when photon = H is found?	Electron "becomes" $\lvert\psi_B\rangle$	We learn the electron was in the $\lvert\psi_B\rangle$ branch

Why no signal can be sent.

The no-signalling theorem (Paper 2 [18], Section 5) states that the *marginal* distribution of the electron is unchanged by any measurement on the photon:

$$\rho(\mathbf{x}_{\text{elec}}) = \int \rho(\mathbf{x}_{\text{elec}},\, s_{\text{photon}})\, ds_{\text{photon}} = \frac{1}{2}|\psi_A|^2 + \frac{1}{2}|\psi_B|^2. \tag{17}$$

This marginal distribution has *no interference fringes* and is *independent of what the photon measurement found*. An observer watching only the electron screen cannot detect any change when the photon is measured, regardless of the measurement outcome or the distance between electron and photon.

Only after the photon measurement result is *classically communicated* (at most at the speed of light) to the electron observer, and the electron data is *post-selected* on the photon outcome, do the sub-ensemble fringes appear or disappear.

Summary.

The appearance of "instant non-local influence" is resolved by recognising that the joint ZPF correlation $\rho(\mathbf{x}_{\text{elec}}, s_{\text{photon}})$ was established at the moment of interaction at the slit. The photon measurement *reveals* which part of this pre-existing correlation we occupy; it does not *create* any new physical influence on the electron. This is Einstein's position vindicated: the correlation is real and pre-existing; the update is epistemic, not physical.

The Delayed-Choice Quantum Eraser

The most striking version of the quantum eraser is the *delayed-choice* experiment [1], in which the decision to measure the marker photon in the which-path basis or the erasing basis is made *after* the electron (or signal photon) has already arrived at the screen. This appears to suggest that a future decision determines a past event—a retrocausal paradox.

The present framework resolves this completely.

The experimental timeline:

t	**Event**	**ZPF framework**
t_0	Photon pair created	Joint ZPF correlation $\rho(\mathbf{x}_s, s_i)$ established
t_1	Signal hits screen	Full data recorded; marginal $\rho(\mathbf{x}_s) = \frac{1}{2}\lvert\psi_A\rvert^2 + \frac{1}{2}\lvert\psi_B\rvert^2$, *no fringes*
$t_2 > t_1$	Idler measurement method chosen	Post-selection criterion decided; no physical effect on signal
$t_3 > t_2$	Idler measured; results compared	Sub-ensemble selected by Bayes; fringes appear in sub-ensemble only

Why there is no retrocausality.

The key observation is that the full signal data recorded at t_1 *never shows interference fringes*—before or after the idler measurement. The fringes appear only in a *sub-ensemble* selected at t_3 by Bayes conditioning on the idler result.

Formally, for all times $t \geq t_0$:

$$\rho(\mathbf{x}_s) = \int \rho(\mathbf{x}_s,\, s_i)\, ds_i = \tfrac{1}{2}|\psi_A|^2 + \tfrac{1}{2}|\psi_B|^2 \quad \text{(no fringes, always).} \tag{18}$$

This is independent of:

- *When* the idler is measured (t_2 can be arbitrarily later than t_1),

- *Whether* the idler is measured at all,
- *Which basis* is chosen for the idler measurement.

What the idler measurement at t_2 does is provide a *classical label* for each signal photon event that was already recorded at t_1. The experimenter then *sorts* the recorded signal data into sub-ensembles:

$$\text{Sub-ensemble } (+45^\circ): \quad \rho(\mathbf{x}_s \,|\, +45^\circ) = |\psi_A + \psi_B|^2 \quad \text{(fringes)}, \tag{19}$$

$$\text{Sub-ensemble } (-45^\circ): \quad \rho(\mathbf{x}_s \,|\, -45^\circ) = |\psi_A - \psi_B|^2 \quad \text{(complementary fringes)}. \tag{20}$$

The two sub-ensembles have complementary fringe patterns that exactly cancel when combined—recovering the no-fringe marginal (18).

The apparent paradox, dissolved.

The delayed-choice quantum eraser does not show that the future affects the past. It shows that:

> *The joint ZPF correlation $\rho(\mathbf{x}_s, s_i)$ was established at the moment of creation t_0. The signal data recorded at t_1 already contained the sub-ensemble structure—it was simply not yet sorted. Sorting at t_3 reveals a structure that was always present, not one that was created by the future measurement.*

This is precisely the same logic as the no-signalling theorem: a distant measurement cannot change the local statistics, only *label* the existing data in a new way. The "retrocausal" appearance is an artefact of the Copenhagen language in which measurement "creates" reality. In the ZPF framework, reality (the joint distribution) was created at t_0; measurement only reveals it.

6.3 Schrödinger's Cat

The same logic applies to Schrödinger's cat: the cat's state is not determined by "observation" but by the physical interaction of the radioactive atom's ZPF with the detector. The detector physically disturbs the ZPF of the atom, triggering the Bayes update. The cat is alive or dead at the moment of physical interaction—not at the moment of human observation.

7 Discussion

7.1 Comparison with Other Interpretations

Interpretation	Which slit?	Why fringes disappear	Status
Copenhagen	Undefined until measured	Wavefunction collapse (no mechanism)	Epistemological, not physical
Many-worlds	Both (in parallel universes)	Decoherence into branches	Unverifiable
de Broglie–Bohm	One slit (guided by pilot wave)	Pilot wave disturbed	Pilot wave origin unexplained
This paper (SED)	**One slit (Nelson SDE)**	**ZPF disturbed (Bayes update)**	**Physical mechanism from Coulomb field**

7.2 Einstein Was Right

Einstein insisted that "God does not play dice"—that quantum probabilities reflect incomplete knowledge of an underlying physical reality, not fundamental indeterminism. The present framework vindicates this intuition precisely: the electron has a definite trajectory, and the probability density $\rho = |\psi|^2$ reflects the distribution over many realisations of the ZPF-driven stochastic process. The randomness is real (the ZPF is a physical field), but the trajectory is definite.

7.3 "The Observer Creates Reality" Is Wrong

The Copenhagen slogan "the observer creates reality" is replaced by the precise statement:

> *The physical interaction required to obtain which-slit information disturbs the ZPF of the electron, changing ρ from $|\psi_A + \psi_B|^2$ to $|\psi_A|^2$. This eliminates the interference term. The observer's consciousness plays no role; only the physical disturbance matters.*

This is fully consistent with the quantum eraser experiments, which show that the fringes can be restored by a second physical interaction ("erasure") regardless of whether any human observer reads the results.

8 Conclusion

We have answered the hundred-year question "which slit does the electron pass through?" within the stochastic electrodynamic framework of Papers 1–6:

1. **The electron passes through one slit.** Its trajectory is definite—a continuous stochastic path described by Nelson's SDE with $D = \hbar/2m$.

2. **The ZPF carries both-slit information.** The electron's Coulomb electromagnetic quantum field fills all space. Its osmotic velocity $u = D\nabla \ln |\psi_A + \psi_B|^2$ guides the electron toward the interference maxima, regardless of which slit it passed through.

3. **Measurement is ZPF disturbance.** Determining which slit requires a physical interaction that disturbs the ZPF. This changes ρ from $|\psi_A + \psi_B|^2$ to $|\psi_A|^2$ by Bayes' theorem, eliminating the interference term and destroying the fringes.

4. **The key equation:**

$$\text{Interference} \iff \text{ZPF undisturbed} \iff \rho = |\psi_A + \psi_B|^2. \tag{9}$$

5. **No new postulates are required.** All ingredients follow from the single postulate of Paper 1: electromagnetic field energy is carried in discrete quanta. The Coulomb field, its ZPF, the diffusion coefficient $D = \hbar/2m$, Nelson's SDE, and Bayes' theorem are all established in Papers 1–3.

The double-slit paradox is not a paradox about the nature of reality or the role of consciousness. It is a straightforward consequence of the non-local structure of the electron's Coulomb ZPF, which carries geometric information about both slits, and of the physical fact that measurement requires interaction that disturbs this field.

Open Question: The Origin of Randomness in Photons

The present paper resolves the double-slit paradox specifically for the *electron*. The physical mechanism is clear: the electron possesses a Coulomb field, and the ZPF arising from this field provides the osmotic velocity $u = D\nabla \ln |\psi|^2$ with diffusion coefficient $D = \hbar/2m$ derived from the Abraham–Lorentz equation (Paper 1).

However, the photon presents a fundamentally different situation:

- The photon carries no electric charge and therefore has no Coulomb field.
- The photon is massless ($m = 0$), so $D = \hbar/2m$ is undefined.
- The Nelson SDE (1) cannot be directly applied to the photon.

Yet the photon also produces an interference pattern in the double-slit experiment, and this pattern disappears when which-slit information is obtained—the same phenomenology as the electron. The mathematical description ($|\psi_A + \psi_B|^2$, Bayes update, etc.) is identical. But the *physical origin* of the randomness must be different.

> **Open question:** *Where does the randomness of photons come from? What is the physical mechanism that produces the photon's stochastic behaviour in the double-slit experiment, in the absence of a Coulomb field and with zero mass?*

One natural candidate is the electromagnetic vacuum ZPF itself: since the photon is a quantum of the electromagnetic field, it propagates through and interacts with the same vacuum fluctuations $u(\omega) \propto \hbar\omega^3$ that provide the ZPF for charged particles. However, the precise mechanism by which this vacuum field produces a diffusion coefficient and an osmotic velocity for a massless, chargeless particle remains an open problem.

The author regards this as a central direction for future work. A complete resolution of the double-slit paradox for *all* quantum particles — not only electrons — will require a stochastic description of the photon that does not rely on the Coulomb field or the Abraham–Lorentz equation.

Acknowledgements

The author thanks Professor Emilio Santos (University of Cantabria) for correspondence on stochastic electrodynamics and its interpretation. This paper is dedicated to the memory of Luis de la Peña (1931–2026), whose lifelong work on stochastic electrodynamics provided the foundation for this series.

References

[1] Y.-H. Kim, R. Yu, S. P. Kulik, Y. Shih, and M. O. Scully, "Delayed 'choice' quantum eraser," *Physical Review Letters* **84**, 1–5 (2000).

[2] C. Ropers *et al.*, "Quantum eraser experiments for the demonstration of entanglement between swift electrons and light," arXiv:2404.11368 (2024). The first quantum eraser experiment performed with free electrons.

[3] F. Ishii, "Stochastic Electrodynamics of the Photon: Maxwell Equations, Malus's Law, and the Origin of Photon Randomness," ai.viXra (2026), Paper 8 of this series.

[4] A. Pais, "Subtle is the Lord...": The Science and Life of Albert Einstein," *Reviews of Modern Physics* **51**, 863–914 (1979); the moon quotation appears on p. 907.

[5] R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics*, Vol. 3 (Addison-Wesley, Reading MA, 1965), Chapter 1.

[6] N. Bohr, "The quantum postulate and the recent development of atomic theory," *Nature* **121**, 580–590 (1928).

[7] H. Everett III, "Relative state formulation of quantum mechanics," *Reviews of Modern Physics* **29**, 454–462 (1957).

[8] D. Bohm, "A suggested interpretation of the quantum theory in terms of hidden variables," *Physical Review* **85**, 166–179 (1952).

[9] E. Nelson, "Derivation of the Schrödinger equation from Newtonian mechanics," *Physical Review* **150**, 1079–1085 (1966).

[10] E. Nelson, *Dynamical Theories of Brownian Motion* (Princeton University Press, 1967).

[11] T. H. Boyer, "Derivation of the blackbody radiation spectrum without quantum assumptions," *Physical Review* **182**, 1374–1383 (1969).

[12] T. H. Boyer, "Random electrodynamics," *Physical Review D* **11**, 790–808 (1975).

[13] M. O. Scully and K. Drühl, "Quantum eraser: A proposed photon correlation experiment concerning observation and delayed choice in quantum mechanics," *Physical Review A* **25**, 2208–2213 (1982).

[14] S. P. Walborn, M. O. Terra Cunha, S. Pádua, and C. H. Monken, "Double-slit quantum eraser," *Physical Review A* **65**, 033818 (2002).

[15] J. A. Wheeler, "The "past" and the "delayed-choice" double-slit experiment," in A. R. Marlow (ed.), *Mathematical Foundations of Quantum Theory* (Academic Press, New York, 1978), pp. 9–48.

[16] E. Santos, "Stochastic electrodynamics and the interpretation of quantum theory," arXiv:1205.0916 (2012, revised 2020).

[17] F. Ishii, "Quantum Mechanics from the Coulomb Field," ai.viXra:2605.0035, Paper 1 of this series (2026); Zenodo: https://doi.org/10.5281/zenodo.20720571.

[18] F. Ishii, "Quantum Entanglement and the Coulomb Force from Electromagnetic Cross-Correlations," ai.viXra:2605.0036, Paper 2 of this series (2026); Zenodo: https://doi.org/10.5281/zenodo.20721869.

[19] F. Ishii, "Ergodicity of ZPF-Driven Stochastic Motion," ai.viXra:2605.0039, Paper 3 of this series (2026); Zenodo: https://doi.org/10.5281/zenodo.20724430.

[20] F. Ishii, “The Dirac Equation from Four-Dimensional Brownian Motion,” ai.viXra:2605.0045, Paper 4 of this series (2026); Zenodo: https://doi.org/10.5281/zenodo.20724538.

[21] F. Ishii, “The Anomalous Magnetic Moment and the Lamb Shift Derived from the Stochastic Coulomb Field: First-Order Calculations,” ai.viXra:2606.0007, Paper 5 of this series (2026); Zenodo: https://doi.org/10.5281/zenodo.20724591.

[22] F. Ishii, “Hydrogen Hyperfine Splitting from the Zero-Point Field,” ai.viXra (2026), Paper 6 of this series; Zenodo: https://doi.org/10.5281/zenodo.20738810.