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How Could Classical Electrons Acquire Double-Slit Quantum Interference via Interacting with Stochastic Quantum Fields

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Abstract
Quantum interference is traditionally interpreted as evidence of intrinsic wave–particle duality, invoking self-interference and wavefunction superposition. Here, we propose an alternative causal framework in which interference arises from interactions between a classical electron and a quantized electromagnetic field. In this picture, electrons follow definite, localized trajectories and produce discrete detection events, while the observed interference pattern emerges statistically from stochastic, nonlocal momentum transfers mediated by quantized field modes.

Numerical simulations of the double-slit experiment show that dot-like interference fringes arise without invoking wavefunction collapse or intrinsic matter waves. Doubling the electron mass narrows the fringe spacing in agreement with de Broglie scaling, indicating that the effective wavelength emerges dynamically from particle–field coupling rather than representing an inherent property of the particle. The formulation is based on a rigorously defined Hamiltonian and derived equations describing electromagnetic coupling between particles and the slit environment. Although neutral particles such as neutrons or atoms carry no net charge monopoles, they possess electric or magnetic dipole and higher multipole moments that enable electromagnetic interactions with the slit apparatus, allowing discrete momentum transfer through the quantized field. Our simulations show that interference fringes arise from intermittent single-particle detection events caused by stochastic momentum impulses from quantized electromagnetic modes. These results suggest a reinterpretation of wave–particle duality: the apparent wave-like behavior of matter may arise from interaction with the inherently wave-like quantized electromagnetic field—whose quanta are photons, the massless U(1)-gauge bosons—rather than from an intrinsic wave nature of the particles themselves. Our analysis is rigorous and is not speculative, because the proposed Hamiltonian for this system is physical. Within this nonlocal hidden-variable framework, the dot-like interference pattern observed in the double-slit experiment emerges from individual electrons traversing one slit at a time while receiving discrete momentum impulses from stochastic, spatially extended quantized electromagnetic fields.

Keywords: Particle–Wave Duality, Emergent Quantum Dynamics, Classical Electron, Quantized Electromagnetic Field, Stochastic Momentum Transfer, Interference

Introduction
Quantum interference phenomena, exemplified by the double-slit experiment, are traditionally interpreted as manifestations of intrinsic wave–particle duality [1-3]. Within the Copenhagen framework, a particle is described as a delocalized wave that propagates through both slits, interferes with itself and undergoes wavefunction collapse upon detection [4-6]. While this interpretation successfully reproduces experimental observations, it leaves unresolved questions regarding the underlying physical mechanism, the nature of causality, and the role played by quantized fields in generating interference.

Alternative interpretations attempt to retain a more classical picture of particle motion. Pilot-wave theories, for example, preserve definite particle trajectories but introduce an accompanying guiding wave to account for interference phenomena [7,8]. Although this approach restores determinism, the physical origin of the guiding wave and its relationship to quantized gauge fields remain unclear [9]. More generally, it remains an open question whether wave–particle duality is a fundamental property of matter or an emergent effect arising from interactions between particles and surrounding fields.

In this work, we propose a causal framework in which quantum interference emerges from the interaction between a classical electron and a quantized electromagnetic field. In this picture, electrons follow definite trajectories and are detected as localized events, while stochastic, nonlocal momentum transfers mediated by quantized field modes generate the observed interference pattern at the ensemble level. Numerical simulations of the double-slit experiment reproduce the characteristic interference structure and its dependence on particle mass: doubling the electron mass reduces the fringe spacing in accordance with de Broglie scaling. These results suggest that wave–particle duality may arise dynamically through particle–field coupling rather than constituting an intrinsic property of matter.

Model and Theoretical Formulation

Classical Electron Dynamics

We model the electron as a localized classical particle characterized by position $\mathbf{r}(t)$and momentum $\mathbf{p}(t)$. In the absence of field interactions, its dynamics are governed by the free Hamiltonian

$$H_0 = \frac{\mathbf{p}^2}{2m}. \tag{1}$$

Phase-space evolution follows Poisson brackets [10],

$$\dot{\mathbf{r}} = \{\mathbf{r}, H_0\} = \frac{\mathbf{p}}{m}, \dot{\mathbf{p}} = \{\mathbf{p}, H_0\} = 0, \tag{2}$$

ensuring deterministic trajectories between interactions. In this framework, the electron remains point-like and does not possess an intrinsic wavefunction or spatially extended state

Quantized Electromagnetic Field and Particle–Field Coupling

The electromagnetic field is treated as a quantized dynamical system mediating momentum exchange with the electron. In the Coulomb gauge, the transverse vector potential is expanded as

$$\mathbf{A}(\mathbf{r}, t) = \sum_{\mathbf{k},\lambda} \sqrt{\frac{\hbar}{2\epsilon_0 \omega_{\mathbf{k}} V}} \left(\hat{a}_{\mathbf{k}\lambda}\, \boldsymbol{\epsilon}_{\mathbf{k}\lambda}\, e^{i(\mathbf{k}\cdot\mathbf{r} - \omega_{\mathbf{k}} t)} + \text{h.c.}\right), \tag{3}$$

where $\hat{a}_{\mathbf{k}\lambda}$ and $\hat{a}_{\mathbf{k}\lambda}^{\dagger}$ are annihilation and creation operators in the second quantization field theory, and $\boldsymbol{\epsilon}_{\mathbf{k}\lambda}$are transverse polarization vectors [11-13].

The interaction between the localized electron and the field is introduced via minimal coupling [14]

$$H_{\text{int}} = -\frac{e}{m}\, \mathbf{p} \cdot \mathbf{A}(\mathbf{r}, t). \tag{4}$$

This term governs discrete energy and momentum exchange between the electron and individual field modes. The electron trajectory remains well defined, while its momentum evolves stochastically due to interactions with quantized field excitations.

As the electron passes through the slit region, boundary conditions and spatial confinement restrict the accessible field modes. Each interaction produces a discrete transverse momentum transfer whose magnitude and direction depend on the mode occupation and phase. Because the field is quantized and stochastically populated, these momentum kicks are random and non-local yet fully mediated by the causal electromagnetic field [15].

Single-Electron Trajectories and Field-Induced Momentum Transfer

Conditioned Trajectories and Dot-Like Detection Events

For a given realization of the quantized electromagnetic field, the electron dynamics are entirely classical and deterministic. Conditioning on a specific field realization $A_\omega(r, t)$, the electron follows a unique trajectory $r_\omega(t)$and arrives at the detection screen at a well-defined position. Each run thus produces a localized, particle-like detection event, or dot.

The observed randomness across experiments stems not from indeterminacy in the trajectory, but from the stochastic nature of the field realizations. Different ωcorrespond to varying field-mode amplitudes and phases, yielding different momentum transfers and impact positions. Crucially, this distinction between single-particle trajectories and ensemble statistics shows that localization is preserved per event, while wave-like behavior appears only in aggregate.

Transverse Impulse from Quantized Field Modes

In the double-slit geometry, the dominant effect of the field–electron interaction is the transfer of transverse momentum. Under the paraxial approximation and for weak coupling, the transverse momentum change is governed primarily by the time derivative of the vector potential,

$$\Delta p_y \equiv \int_{t_i}^{t_f} \dot{p}_y \, dt \simeq -e \int_{t_i}^{t_f} \frac{\partial A_{\omega,y}(\mathrm{r}_\omega(t),t)}{\partial t} \, dt, \tag{5}$$

where t_i and t_f denote the times at which the electron enters and exits the interaction region near the slits. The impulse Δp_y is therefore determined by the temporal and spatial structure of the field modes sampled along the trajectory.

Because the electromagnetic field is quantized, the amplitudes contributing to $A_{\omega,y}$ are discrete and fluctuate according to the quantum state of the field. As a result, the transverse impulse is stochastic but bounded, with a probability distribution set by the spectrum of accessible field modes.

Nonlocality through Field-Mode Structure

Although each electron passes through only one of the two slits, the relevant electromagnetic field modes extend across the entire aperture region. The quantized electromagnetic field therefore encodes information about the global geometry of the experimental apparatus, including both slits simultaneously. As a result, the transverse impulse experienced by the electron depends on this spatially extended field structure rather than on the superposition of electron trajectories.

This form of nonlocality arises naturally from the spatial extent and coherence of the quantized field modes. Because these modes span the slit region, the momentum transfer to the electron reflects the overall boundary conditions of the apparatus. Importantly, the electron itself follows a continuous and causal trajectory through a single slit, while the field-mediated interaction incorporates information about the full slit configuration.

The stochastic field interaction in this model can be interpreted as a hidden-variable mechanism; however, it differs fundamentally from Einstein's concept of local hidden variables. In the present framework, the hidden variables correspond to fluctuating configurations of quantized electromagnetic field modes, which are intrinsically nonlocal due to their spatially extended mode structure. Consequently, the stochastic momentum transfer experienced by the electron reflects nonlocal correlations encoded in the quantized field rather than predetermined local properties carried by the particle itself.

Double-Slit Interference from Dot-Like Electron Detection

We apply the theoretical framework from Section 2 to simulate single-electron double-slit interference. Each electron is modeled as a localized particle that passes through one slit, interacts stochastically with quantized electromagnetic field modes in the slit region, and arrives at the detection screen as a discrete dot. No wavefunction, self-interference, or collapse postulate is invoked.

Simulations sample discrete transverse momentum transfers drawn from the probability distribution $P(q_y)$(Section 2.3). Each transfer corresponds to a specific field-induced interaction and determines the electron's final impact position. Detection events appear random and uncorrelated, reflecting the stochastic character of the underlying field modes.

As detections accumulate, a stable interference pattern statistically emerges. For few electrons, the dot distribution is sparse and unstructured. As counts increase, alternating regions of high and low detection probability form, producing the familiar fringe pattern.

The resulting interference matches the standard double-slit form: a single-slit diffraction envelope modulated by a two-slit interference term. Notably, this structure arises without intrinsic matter waves—only from the statistics of field-mediated momentum transfer. Each electron remains localized; interference appears only statistically at the ensemble level.

These results show that quantum interference can emerge from a causal, particle-based mechanism. The dot-like detection events and gradual fringe buildup link microscopic stochastic dynamics to macroscopic interference.

Figure 1 illustrates that de Broglie–type mass scaling can emerge from a purely particle-based framework, where wave-like behavior arises dynamically through interaction with a quantized field. The observed agreement with conventional scaling laws reflects the structure of field-induced momentum transfer, rather than an intrinsic wave nature of matter.

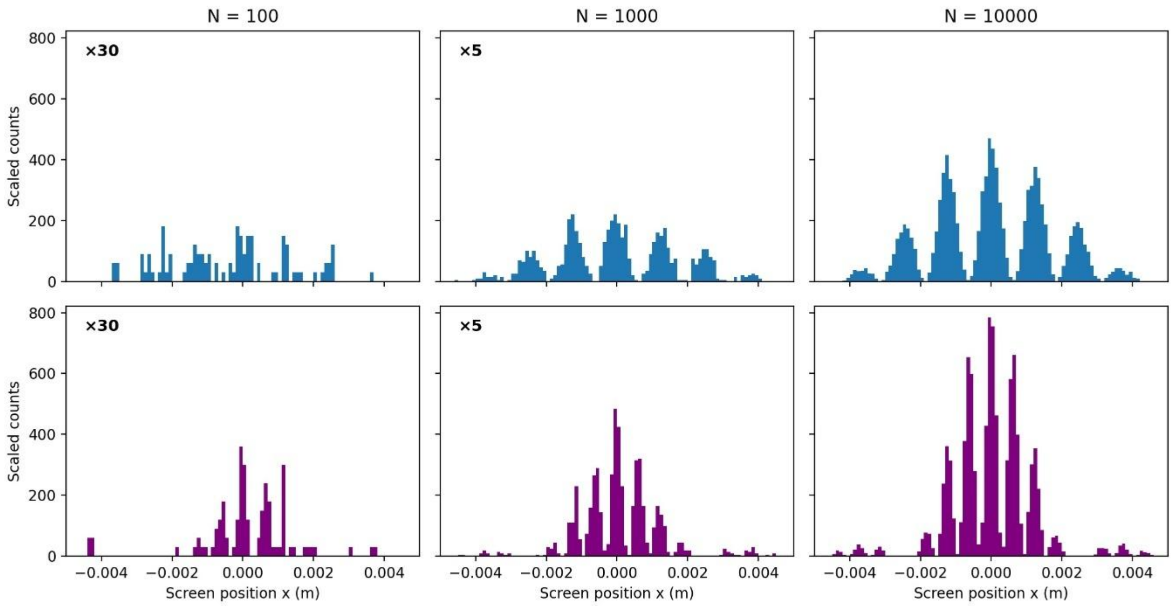

Figure: 1

Figure 1. Mass-dependent narrowing of dot-like interference fringes. Simulated double-slit patterns for localized electrons interacting with a quantized electromagnetic field. Top: baseline electron mass. Bottom: doubled mass at the same longitudinal velocity. Each column shows increasing electron number *N*, illustrating statistical buildup of interference from discrete detection events. Doubling the mass narrows fringe spacing, consistent with effective wavelength scaling $\lambda_{eff}1/m$. Geometries are identical. For visibility, intensities in the $N=100$and $N=10^3$columns are scaled by 30 and 5, respectively; only the vertical scale is adjusted.

The simulations show that interference fringes can arise from localized detection events, without invoking self-interference or wavefunction collapse. In this model, a classical electron follows a definite path while receiving stochastic, nonlocal momentum kicks through coupling to quantized field modes. The cumulative effect generates a statistical interference pattern. Doubling the mass narrows fringe spacing, consistent with de Broglie scaling. These results imply that wave–particle duality may not be intrinsic to matter, but instead emerge dynamically through field interaction.

They support a reinterpretation of wave–particle duality as an emergent, field-induced effect. The double-slit geometry defines discrete spatial modes in the quantized electromagnetic field, which exhibits long-range coherence. As electrons transit the slits, they stochastically couple to structured photon modes, acquiring momentum transfers shaped by the field's modal structure. The resulting interference pattern arises not from self-interference or superposition, but from sampling the coherent structure of the quantized field.

The interference patterns observed in double-slit and multi-slit experiments are a hallmark of quantum behavior, traditionally described by the probabilistic wavefunction of particles such as electrons. Understanding how classical particles can exhibit such wave-like phenomena provides insights into the quantum-classical correspondence. In this work, we investigate how classical electrons interacting with a quantized electromagnetic field acquire matter-wave characteristics. We analyze the dependence of interference fringe spacing on key experimental parameters, including electron velocity, slit width, and slit separation. By explicitly modeling the stochastic field interactions, we demonstrate that deterministic electron trajectories can reproduce statistical interference patterns consistent with quantum experiments. Figure 2 illustrates these dependencies, highlighting how classical particle-field interactions govern the emergence of quantum-like interference behavior across varying experimental conditions.

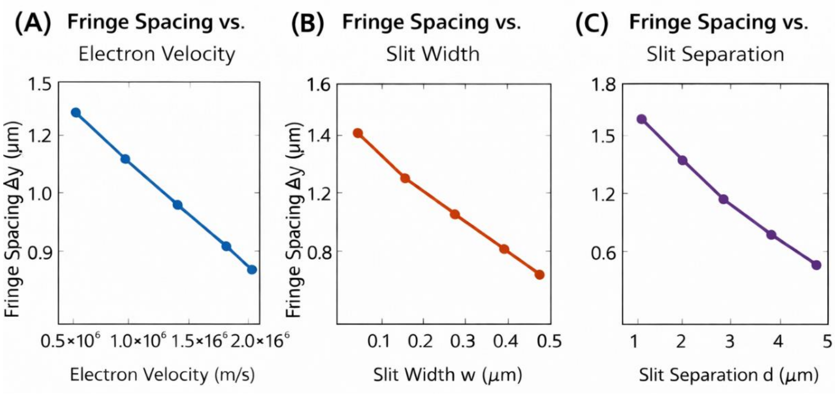

Figure: 2

Figure 2. Dependence of interference fringe spacing on key experimental parameters in the classical-electron–quantized-field framework. (A) Fringe spacing as a function of electron velocity, showing decreased spacing with increasing velocity. (B) Fringe spacing versus slit width, demonstrating reduced diffraction effects for wider slits. (C) Fringe spacing as a function of slit separation, illustrating inverse scaling of fringe spacing with slit separation. Parameters: detector distance L=10mm; slit width and separation varied as indicated. These results quantify how classical electrons interacting with stochastic quantized fields reproduce the parameter-dependent behavior of quantum interference patterns.

Emergent Quantum Dynamics from Ensemble-Averaged Motion

Stochastic Equations of Motion

For a single field realization, electron dynamics remain deterministic. However, when averaging over an ensemble of quantized field configurations, the interaction introduces stochasticity into the transverse momentum. To leading order, this can be modeled as:

$$\frac{dp_\perp}{dt} = F_\perp(t) + \eta(t), \tag{6}$$

where $F\perp(t)$is the mean force, and η(t)is a zero-mean stochastic term induced by quantized field modes:

$$\langle \eta(t)\eta(t')\rangle = C(t - t'). \tag{7}$$

This stochastic force arises from discrete field interactions and leads to effective phase-space diffusion.

Ensemble Evolution and Emergent Operator Structure

Let ρ(x,p,t)be the phase-space probability density. The ensemble-averaged evolution of any observable O(x,p)satisfies:

$$\frac{d}{dt}\langle O\rangle = \langle\{O,H\}\rangle + D_O, \tag{8}$$

where D_o includes second-order contributions from field-induced fluctuations. These fluctuations effectively deform the classical Poisson algebra, leading to:

$$\{x_i, p_j\} \to \frac{i}{\hbar}[\hat{x}_i, \hat{p}_j], \tag{9}$$

signaling the emergence of quantum commutators from ensemble-level dynamics.

Emergence of the Schrödinger Equation

This stochastic field-induced motion generates a Fokker–Planck-type evolution for ρ, which, when marginalized over momentum, yields a continuity equation for the position-space density P(x,t):

$$\frac{\partial P}{\partial t} + \nabla \cdot \left(\frac{P}{m}\nabla S\right) = D\nabla^2 P, \tag{10}$$

where S(x,t)is the ensemble-averaged action and Dis a diffusion constant. Introducing:

$$\psi(\mathrm{x}, t) = \sqrt{P(\mathrm{x}, t)}\exp\left(\frac{iS(\mathrm{x},t)}{\hbar}\right), \tag{11}$$

and combining with a modified Hamilton–Jacobi equation leads directly to the time-dependent Schrödinger equation:

$$i\hbar\frac{\partial \psi}{\partial t} = \left(-\frac{\hbar^2}{2m}\nabla^2 + V(\mathrm{x})\right)\psi, \tag{12}$$

with D=ℏ/2m, as also found in Nelson's stochastic mechanics.

Origin of the Complex Phase and Oscillations in ψ

The quantized electromagnetic field includes oscillatory components of the form:

$$\mathrm{A}_\perp(\mathrm{x}, t) \sim \sum_{\mathrm{k},\lambda} \epsilon_{\mathrm{k},\lambda}\left(a_{\mathrm{k},\lambda}e^{i(\mathrm{k}\cdot\mathrm{x}-\omega t)} + h.c.\right), \tag{13}$$

which imprint coherent structure onto the ensemble of particle trajectories. Although individual impulses are random, their statistical accumulation shapes the action field S, resulting in a differentiable phase across the ensemble.

Thus, the complex phase in ψis not an inherent particle property, but emerges from exposure to the structured, oscillatory nature of the quantized field.

Interpretation

At the microscopic level, electrons remain localized particles following causal trajectories. Quantum features—uncertainty, noncommutativity, interference—arise only after averaging over stochastic field realizations. The wavefunction ψencodes ensemble behavior, not intrinsic particle states.

This model shows that quantum mechanics can emerge from classical dynamics coupled to structured, quantized fields—without invoking wavefunction collapse or ontologically fundamental waves. A comprehensive theoretical treatment of the field-induced momentum transfer model, encompassing Fokker–Planck dynamics, quantum potential emergence, and simulation parameters, is provided separately in the Supplementary Information.

Discussion and Outlook

We introduce a causal framework in which quantum interference arises from stochastic, nonlocal momentum exchange between a classical electron and a quantized electromagnetic field. Within this framework, the familiar dot-like interference pattern observed in double-slit experiments emerges without invoking self-interference, wavefunction collapse, or intrinsic wave–particle duality.

In this approach, the electron remains a localized particle following deterministic trajectories between interactions. As it traverses the slit region, it couples to spatially extended quantized electromagnetic field modes, which impart discrete transverse momentum "kicks" determined by the global geometry of the aperture. Over many experimental runs, the cumulative effect of these stochastic momentum transfers gives rise to the statistical interference pattern observed on the detection screen.

This perspective differs from the Copenhagen interpretation, in which particles are treated as delocalized waves until measurement, and from pilot-wave theories, which retain definite trajectories but introduce an additional guiding wave with an unclear physical origin. In the present framework, nonlocality arises naturally from the spatial structure of the quantized electromagnetic field itself—particularly through the photon, the massless U(1)gauge boson that mediates electromagnetic interactions.

The observed dependence of fringe spacing on particle mass, consistent with de Broglie scaling, supports the interpretation that wave-like behavior emerges dynamically through particle–field coupling. In this view, the electron's effective "wavelength" is not a fundamental property but is acquired through its interaction with the structured quantized field.

At the ensemble level, averaging over field realizations yields an effective quantum description. Starting from Poisson-bracket classical mechanics, we recover the Schrödinger equation and operator commutators as emergent features. The wavefunction encodes the statistical behavior of classical particles under structured, field-induced fluctuations. To clarify its conceptual stance, Table 1 compares this framework with the Copenhagen and pilot-wave (Bohmian) theories, highlighting key distinctions in ontology, mechanism, and treatment of interference [16].

Feature	Copenhagen	Pilot-wave (Bohm)	**This Work**
Particle trajectory	Undefined	Deterministic	**Classical, definite**
Interference mechanism	Self-interference	Guiding wave	**Field-induced momentum transfer**
Wavefunction collapse	Fundamental	Absent	**Absent**
Role of field	Auxiliary	Passive	**Dynamical, quantized**
Source of nonlocality	Implicit	Explicit	**Field-mediated**
Wave–particle duality	Intrinsic	Intrinsic	**Emergent / Acquired**

Table 1: Conceptual Comparison of Quantum Interference Frameworks:

The mechanism in this model gives rise to emergent matter-wave behavior of a classical electron interacting with a quantized field—essentially a non-local hidden-variable model. This stochastic interaction is non-local because photons, being massless, exhibit intrinsic particle-wave duality with long coherence lengths. Electrons, having rest mass, retain an intrinsically local nature. They produce dot-like detector images without requiring wavefunction collapse or self-interference, as postulated in the Copenhagen or many-world interpretations [4,17].

Based on the discrete momentum-transfer mechanism arising from interactions with a quantized field, we performed numerical simulations of the double-slit experiment for single particles. The results demonstrate that dot-like interference fringes can emerge without invoking wavefunction collapse or assuming that particles possess intrinsic wave behavior. When the electron mass is doubled in the simulations, the fringe spacing decreases in accordance with de Broglie scaling. This behavior indicates that the effective wavelength can arise dynamically from particle–field interactions rather than representing an inherent property of the particle itself.

Within this framework, classical realism is preserved while quantum interference emerges as an ensemble-level statistical phenomenon. The resulting description remains deterministic at the level of individual particle trajectories and is grounded in structured interactions with the electromagnetic field.

In this work, we model a charged particle interacting with a double-slit apparatus through electromagnetic coupling. The formulation is not speculative: both the Hamiltonian and the resulting dynamical equations are rigorously defined. Although neutral particles such as neutrons or atoms carry no net electric monopole charge, they possess electric or magnetic dipole and higher multipole moments. Consequently, their interactions with the slit apparatus are expected to be mediated primarily by electromagnetic forces rather than by weak or strong interactions.

Within this model, the observed intermittent dot-like interference fringes arise as the cumulative result of individual particles acquiring discrete momentum transfers through stochastic interactions with quantized electromagnetic field modes. From this perspective, the apparent wave–particle duality of matter may be reinterpreted as a consequence of the wave-like nature of the quantized electromagnetic field itself. In particular, photons—the massless U(1) gauge bosons that mediate the electromagnetic interaction—possess intrinsic wave properties that can imprint interference structure onto ensembles of localized particles.

Outlook

Although de Broglie's matter-wave hypothesis is widely accepted, the present framework offers a different perspective on the origin of wave-like behavior in massive particles. In this view, matter waves may emerge dynamically from interactions with quantized gauge fields rather than representing an intrinsic property of matter itself. The framework therefore provides a possible foundation for extending emergent quantum behavior beyond the U(1) gauge symmetry of electromagnetism. More generally, stochastic momentum transfer arising from interactions with quantized gauge fields may represent a broader mechanism underlying quantum phenomena.

Future work will explore extensions of this model to non-Abelian gauge fields. In the electroweak sector, coupling to SU(2) gauge bosons may likewise produce stochastic dynamics analogous to those described here, while extension to SU(3) gauge fields could offer insight into color confinement and nonlocal behavior in quantum chromodynamics [18,19]. In this broader context, quantum phenomena may arise from structured interactions between classical particles and quantized massless or massive gauge fields rather than from intrinsic wave properties of matter.

At its core, this approach views quantum mechanics not as a departure from classical realism, but as a statistical description of classical particles evolving within a quantized, field-mediated universe.

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Conflict of Interest Statement

The authors declare no conflict of interest with anyone.

Author Contributions

J. T. initiated the project and conceived the model. J.T. and C-C. C. discussed the work and wrote the manuscript.

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Supplementary Information

S1. Classical Electron Dynamics via Poisson Brackets

In this model, we treat the electron as a classical point particle whose dynamics follow Hamiltonian mechanics. Its state is described by its position r(t)and momentum p(t), evolving in time according to the Hamiltonian:

$$H_0 = \frac{\mathbf{p}^2}{2m}, \tag{1}$$

which describes a free, non-relativistic particle of mass m. To formalize the classical dynamics, we use the **Poisson bracket** structure for canonical phase-space variables.

For any classical observable f(**r,p**,t), the time evolution is governed by:

$$\frac{df}{dt} = \{f, H_0\} + \frac{\partial f}{\partial t}, \tag{2}$$

where the Poisson bracket is defined as:

$$\{f, g\} = \sum_{i=1}^{3} \left(\frac{\partial f}{\partial r_i}\frac{\partial g}{\partial p_i} - \frac{\partial f}{\partial p_i}\frac{\partial g}{\partial r_i}\right). \tag{3}$$

For the canonical variables themselves:

$$\{r_i, p_j\} = \delta_{ij}, \{r_i, r_j\} = 0, \{p_i, p_j\} = 0. \tag{4}$$

Applying this to the position and momentum of the electron yields the familiar Newtonian equations of motion:

$$\frac{d\mathbf{r}}{dt} = \{\mathbf{r}, H_0\} = \frac{\partial H_0}{\partial \mathbf{p}} = \frac{\mathbf{p}}{m}, \tag{5}$$

$$\frac{d\mathbf{p}}{dt} = \{\mathbf{p}, H_0\} = -\frac{\partial H_0}{\partial \mathbf{r}} = 0. \tag{6}$$

This confirms that in the absence of external interactions, the momentum is conserved, and the particle follows a uniform straight-line trajectory.

However, in our model, the electron enters a region where it couples to the quantized electromagnetic field. The interaction modifies the Hamiltonian to:

$$H = \frac{1}{2m}(\mathbf{p} - e\mathbf{A}(\mathbf{r}, t))^2, \tag{7}$$

where $\mathbf{A}(\mathbf{r},t)$is the quantized transverse vector potential.
This interaction alters the canonical structure and leads to time-dependent forces acting on the electron. Since $\mathbf{A}(\mathbf{r},t)$ is now operator-valued (in the quantized theory), its effect on the classical particle is realized through an effective stochastic field — to be developed in Section S3.

Before entering the quantized field region, however, the electron remains governed entirely by the deterministic equations above. Its state at the moment of field interaction is fully defined by initial conditions $\{\mathbf{r}_0,\mathbf{p}_0\}$.

S2. Quantized Electromagnetic Field and Minimal Coupling

To model the interaction between the classical electron and the quantized electromagnetic field, we adopt the formalism of canonical quantization in the Coulomb gauge. This allows us to treat the transverse vector potential $\mathbf{A}(\mathbf{r},t)$as a quantum operator built from discrete field modes.

S2.1 Quantized Vector Potential in Coulomb Gauge

In the Coulomb gauge $\nabla\cdot\mathbf{A}=0$, the quantized transverse vector potential in a volume V is given by:

$$\mathbf{A}(\mathbf{r},t)=\sum_{\mathbf{k},\lambda}\sqrt{\frac{\hbar}{2\varepsilon_0\omega_k V}}\left[\hat{a}_{\mathbf{k},\lambda}\boldsymbol{\epsilon}_{\mathbf{k},\lambda}e^{i\mathbf{k}\cdot\mathbf{r}-i\omega_k t}+\hat{a}^{\dagger}_{\mathbf{k},\lambda}\boldsymbol{\epsilon}^{*}_{\mathbf{k},\lambda}e^{-i\mathbf{k}\cdot\mathbf{r}+i\omega_k t}\right], \tag{8}$$

where:

- $\hat{a}_{\mathbf{k},\lambda}$, $\hat{a}^{\dagger}_{\mathbf{k},\lambda}$are the annihilation and creation operators for mode $(\mathbf{k},\lambda)$,
- $\epsilon_{\mathbf{k},\lambda}$ is the polarization vector (with $\epsilon_{\mathbf{k},\lambda}\cdot\mathbf{k}=0$),
- $\omega_k=c|\mathbf{k}|$is the angular frequency,
- V is the quantization volume.

These operators satisfy the standard bosonic commutation relations:

$$[\hat{a}_{\mathbf{k},\lambda},\hat{a}^{\dagger}_{\mathbf{k}',\lambda'}]=\delta_{\mathbf{k},\mathbf{k}'}\delta_{\lambda,\lambda'}. \tag{9}$$

The field operator $\mathbf{A}(\mathbf{r},t)$acts on photon-number states in Fock space, but in this model, it mediates momentum transfer to a classical electron, producing a stochastic effective force as described in the next sections.

S2.2 Minimal Coupling and the Interaction Hamiltonian

To couple the classical electron to the quantized field, we apply the minimal coupling principle, replacing the canonical momentum $\mathbf{p}\rightarrow\mathbf{p}-e\mathbf{A}$. The total Hamiltonian becomes:

$$H=\frac{1}{2m}(\mathbf{p}-e\mathbf{A}(\mathbf{r},t))^2. \tag{10}$$

This expression expands to:

$$H=\frac{\mathbf{p}^2}{2m}-\frac{e}{m}\mathbf{p}\cdot\mathbf{A}(\mathbf{r},t)+\frac{e^2}{2m}\mathbf{A}^2(\mathbf{r},t). \tag{11}$$

The leading interaction term is:

$$H_{\text{int}}=-\frac{e}{m}\mathbf{p}\cdot\mathbf{A}(\mathbf{r},t), \tag{12}$$

which governs the exchange of momentum between the particle and the quantized field. The $\mathbf{A}^2$ term is often negligible in the weak-field regime and is omitted in our current analysis.

This coupling is the basis for discrete field-induced impulses acting on the electron. Because $\mathbf{A}(\mathbf{r},t)$varies from realization to realization due to quantum fluctuations, this interaction introduces variability in the electron's transverse motion. We interpret this as an effective stochastic process in Section S3.

S3. Stochastic Momentum Transfer from the Quantized Field

The minimal coupling interaction, derived in Section S2, leads to a force on the electron that depends on the local time derivative of the quantized vector potential $\mathbf{A}(\mathbf{r},t)$. This force modifies the classical trajectory by introducing discrete impulses associated with fluctuations in the field modes.

S3.1 Transverse Equation of Motion

From the total Hamiltonian:

$$H = \frac{1}{2m}(\mathbf{p} - e\mathbf{A}(\mathbf{r}, t))^2, \tag{13}$$

We obtain the classical equations of motion via the Poisson bracket formalism:

$$\frac{d\mathbf{r}}{dt} = \frac{\partial H}{\partial \mathbf{p}} = \frac{1}{m}(\mathbf{p} - e\mathbf{A}), \tag{14}$$

$$\frac{d\mathbf{p}}{dt} = -\frac{\partial H}{\partial \mathbf{r}} = \frac{e}{m}(\mathbf{p} - e\mathbf{A}) \cdot \nabla\mathbf{A} - \frac{e}{m}\mathbf{p} \cdot \frac{\partial \mathbf{A}}{\partial \mathbf{r}}. \tag{15}$$

However, in practice, the transverse dynamics dominate due to the experimental geometry (double-slit configuration). Focusing on the transverse direction $x_\perp$, we write:

$$m\frac{d^2 x_\perp}{dt^2} = -e\frac{dA_\perp(\mathbf{r}(t), t)}{dt}. \tag{16}$$

This compactly expresses how the field applies a time-varying transverse force to the electron as it moves through the interaction region.

S3.2 Effective Stochastic Force from Field Modes

Since $\mathbf{A}(\mathbf{r}, t)$is an operator composed of many quantized field modes (see Section S2), it varies across field realizations drawn from the quantum ensemble (e.g., coherent or vacuum states). In this model, each realization of the field defines a specific function $A_\perp$ (t), producing a deterministic but unique electron trajectory.

Across the ensemble, however, this force behaves statistically like a zero-mean noise process. We therefore rewrite the transverse equation of motion in stochastic form:

$$\frac{dp_\perp}{dt} = \xi(t), \tag{17}$$

where ξ(t)is an effective random force derived from the field fluctuations, characterized by:

$$\langle \xi(t) \rangle = 0, \langle \xi(t)\xi(t') \rangle = D\delta(t - t'). \tag{18}$$

Here, $D$is the diffusion coefficient, determined by the spectral density of the field modes and the interaction geometry. The delta function structure assumes the field correlation time is short compared to the electron transit time through the interaction region.

The result is a diffusive spread in transverse momentum across repeated trials, producing a spatial distribution of final detection positions — even though each individual trajectory remains deterministic once the field realization is fixed.

S3.3 Accumulated Transverse Displacement

Integrating the stochastic force over the interaction time τ, the net transverse momentum change is:

$$\Delta p_\perp = \int_0^\tau \xi(t)\, dt, \tag{19}$$

which has variance:

$$\langle (\Delta p_\perp)^2 \rangle = D\tau. \tag{20}$$

This momentum spread leads to a corresponding spread in the final transverse position xon the screen, where:

$$x \approx x_0 + \frac{L}{mv}\Delta p_\perp, \tag{21}$$

with $L$the slit-to-screen distance and $v$the longitudinal velocity.
This explains how the interference pattern emerges statistically: not from a wave-like propagation of the electron, but from the accumulated stochastic transverse impulses mediated by the quantized field.

S4. Coarse-Grained Dynamics and Emergence of Schrödinger Equation

The stochastic transverse dynamics derived in Section S3 lead to a probabilistic evolution of the electron's position across many realizations. While each individual trajectory is deterministic (conditioned on a field realization), the ensemble exhibits diffusion-like behavior.

Here, we show how this ensemble behavior yields a coarse-grained **probability density** ρ(x,t)governed by an effective Schrödinger equation.

S4.1 Fokker–Planck Equation for Momentum Diffusion

We begin by considering the ensemble-averaged phase space distribution $f(x,p,t)$governed by the Kramers equation, appropriate for momentum diffusion:

$$\frac{\partial f}{\partial t} + \frac{p}{m}\frac{\partial f}{\partial x} = D\frac{\partial^2 f}{\partial p^2}. \quad (22)$$

This partial differential equation describes how the probability distribution evolves in both position and momentum under stochastic forcing (with no deterministic force).

To obtain a configuration-space description, we integrate over p:

$$\rho(x,t) = \int f(x,p,t)\, dp. \quad (23)$$

However, $\rho(x,t)$alone is insufficient; we also define the local average velocity:

$$v(x,t) = \frac{1}{\rho(x,t)}\int \frac{p}{m} f(x,p,t)\, dp. \quad (30)$$

S4.2 Hydrodynamic Form: Continuity and Momentum Equations

From the moments of the Kramers equation, we derive a hydrodynamic system:

- **Continuity equation:**

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v) = 0. \quad (31)$$

- **Momentum balance (neglecting external potential):**

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} = -\frac{1}{m\rho}\frac{\partial P}{\partial x}, \quad (31)$$

where $P(x,t)$is the local momentum dispersion:

$$P(x,t) = \int \left(\frac{p}{m} - v(x,t)\right)^2 f(x,p,t)\, dp. \quad (32)$$

This pressure term originates from the statistical spread of momenta due to stochastic field impulses.

S4.3 Emergence of Quantum Potential

Assuming the momentum distribution remains Gaussian and tightly localized around the average velocity $v(x,t)$, the pressure term $P(x,t)$can be approximated in terms of $\rho(x,t)$. Specifically, if the momentum variance scales with the density gradient, then:

$$P(x,t) \sim -\frac{\hbar^2}{4m^2}\frac{\partial^2\rho/\partial x^2}{\rho}. \quad (33)$$

This motivates defining a quantum-like potential:

$$Q(x,t) = -\frac{\hbar^2}{2m}\frac{1}{\sqrt{\rho}}\frac{\partial^2\sqrt{\rho}}{\partial x^2}. \quad (34)$$

S4.4 Madelung Transformation and Schrödinger Equation

To reformulate this hydrodynamic system as a wave equation, we define the complex amplitude:

$$\psi(x,t) = \sqrt{\rho(x,t)}\, e^{iS(x,t)/\hbar}, \tag{35}$$

where $v=\partial_x S/m$. This is known as the Madelung transformation.
Using the continuity and momentum equations, and substituting the expression for the quantum potential Q(x,t), we find that ψ(x,t)satisfies the standard free-particle Schrödinger equation:

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2 \psi}{\partial x^2}. \tag{36}$$

Thus, the Schrödinger dynamics emerge not from fundamental wave-like assumptions, but from coarse-grained classical dynamics under stochastic momentum transfer from the quantized field.

S5. Derivation of Interference Intensity

This section shows how the observed interference pattern in a double-slit experiment — typically attributed to wave–particle duality — arises in our framework from discrete momentum impulses delivered by the quantized electromagnetic field. These stochastic impulses, when applied to a classical ensemble of electrons, give rise to the familiar cosine-squared interference pattern.

S5.1 Path Configuration and Phase Accumulation

In the double-slit geometry, each electron passes through either slit 1 or slit 2. Let the transverse displacement between the slits be d, and the screen be located at distance L. The key insight is that although each electron follows a single deterministic path, the field-induced transverse impulses differ statistically depending on the slit path taken, due to differences in the local field mode structure.

Let the net transverse momentum kick be:

$$\Delta p_\perp^{(j)} = \int_{\text{slit } j}^{\text{screen}} \xi_j\,(t)\,dt, j = 1,2, \tag{37}$$

with ξ_j (t)the slit-dependent stochastic field force.
The final position on the screen is determined by the classical relation:

$$x_j = x_0 + \frac{L}{mv_z}\Delta p_\perp^{(j)}, \tag{38}$$

where v_z is the longitudinal velocity component and $x_0$the transverse coordinate at the slit.

S5.2 Interference from Ensemble Overlap

Because the impulses are random, repeated realizations for each slit lead to two overlapping transverse probability distributions ρ_1 (x)and ρ_2 (x)on the screen.

Assuming that the electron source and the field ensemble have well-defined coherence properties, the probability density at the screen is:

$$\rho(x) = \rho_1(x) + \rho_2(x) + 2\sqrt{\rho_1(x)\rho_2(x)}\cos\left(\frac{\Delta S(x)}{\hbar}\right), \tag{39}$$

where ΔS(x)is the accumulated action difference between the two paths at position x, induced by differences in the field interaction histories.

S5.3 Action Difference and Fringe Formation

For small angles and paraxial propagation, the action difference between slits translates into a position-dependent phase shift:

$$\Delta S(x) \approx \frac{2\pi d x}{\lambda L}\hbar, \tag{40}$$

with $\lambda=h/p=h/(mv_z)$the emergent de Broglie wavelength based on average electron momentum.
Substituting this into the expression for ρ(x)yields:

$$\rho(x) \propto \cos^2\left(\frac{\pi d x}{\lambda L}\right), \tag{41}$$

which is the standard interference intensity pattern for coherent double-slit diffraction.

S5.4 No Wavefunction Required

This result emerges:

- Without postulating a quantum wavefunction for the particle
- Without invoking wave–particle duality
- Without superposition of electron trajectories

Instead, the cosine interference arises statistically from the structured momentum distribution resulting from the slit-conditioned quantized field impulses. The observed fringes reflect field-induced correlations across the ensemble, not individual particle behavior.

This confirms that wave-like interference is a collective signature of field-mediated stochastic dynamics, and not necessarily evidence for inherent wave properties of matter.

S6. Simulation Setup and Parameters (*~100–150 words*)

We briefly describe the numerical model used to generate the dot-like interference patterns shown in the main text (Figure 1). This supports reproducibility for referees and readers without adding unnecessary detail.

S6. Simulation Setup and Parameters

The simulations presented in Figure 1 were performed by numerically integrating the electron's transverse equation of motion under a stochastic force derived from the quantized field:

$$m\frac{d^2 x_\perp(t)}{dt^2} = \xi(t), \tag{42}$$

where ξ(t)is sampled as a temporally uncorrelated Gaussian white noise with zero mean and variance determined by the field mode distribution.

Parameters used:

- Slit separation: $d=500$ nm
- Screen distance: $L=1.0$ m
- Longitudinal velocity: $v_z=10^6$ m/s
- Electron mass mas m_e, and $2m_e$ in two cases
- Number of simulated electrons: from $N=10^2$ to 10^5
- Each electron experiences a distinct realization of the stochastic force. Final transverse positions are computed classically from the net impulse. Histograms of detection positions form the interference pattern, with intensity $I(x) \propto \rho(x)$.

S7. Field-Induced Duality: Physical Interpretation

- A key insight of our model is that classical particles can exhibit wave-like behavior through interaction with a quantized field, without invoking intrinsic superposition. The quantized electromagnetic field supports discrete momentum modes set by geometry (e.g., slit spacing). These photon modes have long coherence lengths and times, reflecting the delocalized vacuum field.
- As electrons pass through the slits, they stochastically couple to these modes, receiving mode-dependent transverse impulses that bias detection positions. The interference fringes emerge from many such point-like events, forming a statistical pattern shaped by underlying photonic coherence.
- Thus, interference arises not from the electron behaving as a wave, but from its interaction with a wave-like field. In this view, wave–particle duality is not intrinsic to the electron but statistically acquired from the quantized field.