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Article

A Dynamical Origin of Wave-Particle Duality from Stochastic Mass-Energy Interconversion

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Abstract

Wave-particle duality remains one of the most striking and conceptually unresolved features of quantum mechanics. Here I present a dynamical mechanism for wave-particle duality based on spontaneous stochastic mass-energy interconversion at subatomic scales. By promoting particle mass to a fluctuating quantity consistent with Einstein’s mass-energy equivalence, I derive a Schrödinger equation with an additional stochastic kinetic-phase term. Applied to the canonical double-slit experiment, the framework shows that quantum interference arises from coherent, path-dependent phase accumulation driven by mass-energy fluctuations, while particle-like localization emerges naturally at detection. The formalism yields closed-form expressions for interference visibility, predicts a momentum- and mass-dependent decoherence rate, admits a path-integral interpretation, and enables direct experimental bounds using neutron, electron, and atom interferometry. The results provide a physically grounded account of wave-particle duality without modifying the axioms of quantum mechanics.

Keywords: wave–particle duality; quantum interference; stochastic dynamics; mass–energy equivalence; quantum decoherence; double-slit experiment

Introduction

The double-slit experiment remains a paradigmatic demonstration of quantum mechanics, revealing interference patterns produced by individual particles detected one at a time. Although the quantum formalism predicts these outcomes with precision, it offers no physical account of how a single particle propagates as a delocalized wave yet registers as a localized detection event.

Standard interpretations treat wave-particle duality as a fundamental postulate, often invoking complementarity or measurement-induced collapse. Such explanations are epistemic rather than dynamical. By contrast, quantum field theory admits fluctuating vacuum energies and transient particle creation, indicating that mass and energy need not be strictly static at the most fundamental level.

A recent framework proposed that quantum uncertainty may arise from spontaneous stochastic mass-energy interconversion at subatomic scales [1]. In this picture, particle mass undergoes rapid fluctuations consistent with Einstein’s mass-energy equivalence, introducing stochasticity directly into quantum dynamics. The present work applies this framework to the double-slit experiment and shows that wave-particle duality emerges naturally from kinetic-phase dynamics.

Stochastic Mass-Energy Dynamics

Fluctuating Mass Hypothesis

I postulate that a particle’s inertial mass fluctuates according to

$$m(t) = m_0 + \delta m(t),$$

where m_0 is the mean rest mass and $\delta m(t)$ is a stationary stochastic process satisfying

$$\langle \delta m(t) \rangle = 0, \quad \langle \delta m(t) \delta m(t') \rangle = \sigma_m^2 \delta(t - t').$$

These fluctuations correspond to spontaneous mass-energy interconversion,

$$\delta E(t) = c^2 \delta m(t),$$

and respect global conservation laws in expectation.

Modified Schrödinger Equation

The time-dependent Hamiltonian becomes

$$H(t) = \frac{p^2}{2m(t)} + V(x),$$

which, expanded to first order in $\delta m(t)$, yields

$$H(t) \approx \frac{p^2}{2m_0} - \frac{p^2}{2m_0^2} \delta m(t).$$

The Schrödinger equation therefore acquires a stochastic kinetic-phase term,

$$i\hbar \frac{\partial \psi}{\partial t} = \left[\frac{p^2}{2m_0} + V(x) - \frac{p^2}{2m_0^2} \delta m(t) \right] \psi.$$

No modification of quantum postulates is required.

Double-Slit Interference

Two-Path State

After the slits, the wavefunction is

$$\psi = \frac{1}{\sqrt{2}} (\psi_1 + \psi_2),$$

and the detected intensity is

$$I = |\psi|^2 = \frac{1}{2} (|\psi_1|^2 + |\psi_2|^2 + 2\text{Re}[\psi_1^* \psi_2]).$$

Stochastic Phase Accumulation

Along each path j , the phase accumulated is

$$\phi_j = \frac{1}{\hbar} \int_0^T \frac{p_j^2}{2m(t)} dt.$$

The interference term depends on the relative phase

$$\Delta\phi = \phi_1 - \phi_2.$$

Interference therefore originates from coherent stochastic kinetic-phase accumulation rather than from abstract probability waves.

Fringe Visibility and Experimental Predictions

Coherence Functional

Define the coherence functional

$$\Gamma = \langle e^{i\Delta\phi} \rangle.$$

The averaged intensity becomes

$$\langle I \rangle = \frac{1}{2} (|\psi_1|^2 + |\psi_2|^2 + 2|\psi_1||\psi_2|\text{Re } \Gamma).$$

Visibility Decay

For Gaussian fluctuations,

$$|\Gamma| = \exp\left(-\frac{\sigma_m^2 p^4 T}{2\hbar^2 m_0^4}\right).$$

This predicts exponential loss of visibility with flight time, momentum-dependent suppression, and weaker decoherence for larger masses.

Path-Integral Formulation

The action becomes

$$S[x(t)] = \int dt \left[\frac{1}{2} m(t) \dot{x}^2 - V(x) \right],$$

where

$$m(t) = m_0 + \delta m(t).$$

The interference cross term yields

$$\langle e^{i(S_1 - S_2)/\hbar} \rangle = \Gamma.$$

Which-Path Detection and Decoherence

Which-path measurements couple to kinetic energy and condition the mass-energy phase, driving $\Gamma \rightarrow 0$. Interference is destroyed dynamically without invoking observer-dependent collapse.

Experimental Bounds

From measured visibility,

$$\sigma_m^2 \leq \frac{2\hbar^2 m_0^4}{p^4 T} \ln\left(\frac{1}{V}\right).$$

Existing neutron interferometry experiments place strong upper limits on the fluctuation strength parameter.

Discussion

This framework reframes wave-particle duality as an emergent dynamical phenomenon rather than a primitive axiom of quantum theory. Allowing inertial mass to fluctuate stochastically in accordance with mass-energy equivalence provides a concrete physical mechanism for the coexistence of delocalized propagation and localized detection.

A central conceptual shift is the relocation of quantum “waviness” from the abstract wavefunction to the kinetic phase accumulated through mass-energy fluctuations. Whereas conventional quantum mechanics attributes interference to superposition without an underlying physical carrier, the present framework traces interference to coherent phase accumulation along spacetime paths driven by correlated variations in kinetic energy.

The model accounts for the dependence of interference visibility on mass, velocity, and flight time, explains the dynamical suppression of interference under which-path detection, and aligns with decoherence theory while supplying a microscopic origin for decoherence rates. The formal structure of quantum mechanics remains unchanged; only the physical interpretation of phase is extended.

Connections to quantum field theory are immediate, as vacuum fluctuations and virtual particle processes already involve transient mass-energy exchanges. The present work suggests that such processes may underpin nonrelativistic quantum phenomena and may provide a bridge toward semiclassical gravity.

The theory is falsifiable. Existing neutron and atom interferometry already impose stringent bounds, and next-generation experiments may decisively test the model.

Conclusions

Wave-particle duality can be understood as a dynamical consequence of spontaneous subatomic mass-energy interconversion. Quantum interference emerges from coherent kinetic-phase dynamics, while particle-like localization arises naturally at detection. The framework eliminates the need for observer-dependent collapse and grounds quantum behavior in objective physical processes operating below current experimental resolution.

During the preparation of this work the author utilized Chat-GPT 5.2 in order to structure this paper and format some equations. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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