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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 conceptually unresolved features of quantum mechanics. Although the quantum formalism predicts interference and localization phenomena with great precision, it provides no physical account of how a single quantum object exhibits both behaviors. In this work, a dynamical mechanism for wave-particle duality is proposed based on spontaneous stochastic mass-energy interconversion at subatomic scales. By allowing inertial mass to fluctuate in accordance with Einstein's mass-energy equivalence, a modified Schrödinger dynamics is obtained in which stochastic variations in kinetic energy generate path-dependent phase accumulation. Applied to the double-slit experiment, the framework shows that quantum interference arises from coherent kinetic-phase dynamics, while particle-like localization emerges naturally at detection without invoking observer-dependent collapse. The formalism yields closed-form expressions for interference visibility, predicts a characteristic dependence of coherence loss on particle mass, momentum, and flight time, and admits a transparent path-integral interpretation. Crucially, the theory is explicitly falsifiable: existing neutron and atom interferometry experiments already place stringent upper bounds on the strength of mass-energy fluctuations, and next-generation interferometers can directly test the predicted scaling. The results provide a physically grounded account of wave-particle duality that preserves the standard quantum formalism while making clear, experimentally testable predictions.

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

1. Introduction

Wave-particle duality lies at the historical and conceptual foundation of quantum mechanics. From the earliest studies of light and matter, experiments have repeatedly shown that entities traditionally regarded as particles can exhibit interference and diffraction, while entities regarded as waves can produce localized, particle-like detection events. The double-slit experiment, first performed with light and later extended to electrons, neutrons, atoms, and even large molecules, remains the clearest illustration of this dual behavior. When particles traverse the apparatus one at a time, an interference pattern nevertheless emerges over many detection events, even though each individual detection is localized.

Quantum mechanics successfully predicts these outcomes through the evolution of the wavefunction and the Born rule. However, the theory does not explain *how* a single particle propagates as a delocalized wave yet produces a localized detection. Interpretations invoking complementarity, wavefunction collapse, or epistemic descriptions of quantum states treat wave-particle duality as a fundamental or observer-dependent feature rather than as the result of an underlying physical mechanism. As a result, the duality itself remains conceptually opaque.

At the same time, quantum field theory reveals that vacuum and matter are intrinsically dynamic. Vacuum fluctuations, transient particle creation, and energy exchange occur even in the absence of real particles. These phenomena suggest that quantities treated as fixed parameters in nonrelativistic quantum mechanics may fluctuate at microscopic scales. Among these quantities is

inertial mass, which relativity identifies as a form of energy through Einstein's mass-energy equivalence. While mass is normally taken to be fixed in quantum mechanics, no fundamental principle forbids small, rapid fluctuations provided conservation laws hold in expectation.

Recent work has proposed that intrinsic quantum uncertainty may originate from spontaneous stochastic mass-energy interconversion at subatomic scales rather than from irreducible indeterminism alone [1]. In this picture, inertial mass fluctuates due to underlying vacuum dynamics, introducing stochasticity directly into the kinetic phase of a quantum system. Importantly, this framework does not modify the axioms of quantum mechanics, but supplements the standard formalism with a physically motivated source of phase dynamics.

The present work applies this framework to wave-particle duality. By analyzing the canonical double-slit experiment, it is shown that quantum interference arises from coherent, path-dependent accumulation of kinetic phase driven by mass-energy fluctuations, while particle-like localization emerges naturally at detection through dynamical decoherence. The result is a concrete, testable account of wave-particle duality consistent with standard quantum mechanics.

2. Stochastic Mass-Energy Dynamics

2.1. Fluctuating Mass Hypothesis

The inertial mass of a particle is postulated to fluctuate in time 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

$$\langle \delta m(t) \rangle = 0,$$

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

These fluctuations correspond to spontaneous mass-energy interconversion,

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

and conserve energy in expectation.

2.2. Modified Schrödinger Equation

The time-dependent Hamiltonian is

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

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

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

The Schrödinger equation then reads

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

The stochastic term introduces a kinetic-phase contribution

$$\delta \phi(t) = -\frac{1}{\hbar} \int \frac{p^2}{2m_0^2} \delta m(t) dt.$$

3. Double-Slit Interference

3.1. Two-Path State

After the slits, the wavefunction is a coherent superposition,

$$\psi(\mathbf{x}, t) = \psi_1(\mathbf{x}, t) + \psi_2(\mathbf{x}, t),$$

with detected intensity

$$I(\mathbf{x}) = |\psi_1|^2 + |\psi_2|^2 + 2 \operatorname{Re}\{\psi_1^* \psi_2\}.$$

3.2. Stochastic Phase Accumulation

Along each path i , the accumulated phase is

$$\phi_i = \frac{1}{\hbar} \int_0^T \frac{p_i^2}{2m(t)} dt,$$

which separates into mean and stochastic parts,

$$\phi_i = \phi_i^{(0)} + \delta\phi_i.$$

The relative phase governing interference is

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

4. Fringe Visibility and Decoherence

Define the coherence functional

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

The ensemble-averaged intensity is

$$\langle I \rangle = |\psi_1|^2 + |\psi_2|^2 + 2 \operatorname{Re}\{\Gamma(T) \psi_1^* \psi_2\}.$$

For Gaussian mass fluctuations,

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

5. Path-Integral Formulation

The action along a path is

$$S = \int_0^T \left[\frac{1}{2} m(t) \dot{x}^2 - V(x) \right] dt,$$

with stochastic contribution

$$\delta S = \int_0^T \frac{1}{2} \dot{x}^2 \delta m(t) dt.$$

The interference cross term becomes

$$\left\langle e^{\frac{i}{\hbar}(S_1-S_2)} \right\rangle = \exp \left[-\frac{\langle (\delta S_1 - \delta S_2)^2 \rangle}{2\hbar^2} \right].$$

6. Which-Path Detection and Decoherence

Which-path measurements couple to kinetic energy and therefore to the stochastic phase, dynamically driving

$$\Gamma(T) \rightarrow 0 \quad \text{as} \quad \sigma_m^2 T \rightarrow \infty.$$

No observer-dependent collapse is required.

7. Comparison with Standard Interpretations

Table 1. Comparison of interpretations.

Aspect	Copenhagen / Complementarity	Many-worlds	Epistemic	This work
Wave-particle duality	Postulate	Branching	Knowledge	Emergent dynamics
Interference origin	Unspecified	Branch coherence	Not physical	Kinetic phase
Collapse	Postulated	None	Update	Decoherence
Ontology	Instrumental	High	Minimal	Single-world
New predictions	No	No	No	Yes

8. Experimental Outlook

From a measured visibility $V(T)$, the fluctuation strength is bounded by

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

Neutron interferometry experiments constrain

$$\sigma_m/m \lesssim 10^{-15},$$

while atom and molecular interferometers can improve these bounds by several orders of magnitude. The predicted scaling differs from environmental decoherence, enabling clean experimental discrimination.

9. Discussion

Wave-particle duality is reframed here as an emergent dynamical phenomenon rather than a primitive axiom. Quantum interference arises from coherent stochastic kinetic-phase accumulation, while localization emerges through phase decoherence. The framework preserves the formal structure of quantum mechanics while providing a physical origin for quantum phase and decoherence. Connections to quantum field theory and semiclassical gravity suggest broader implications.

10. Conclusion

Wave-particle duality can be understood as a consequence of spontaneous stochastic mass-energy interconversion. Interference emerges from coherent kinetic-phase dynamics, while particle-like localization arises naturally at detection. The framework removes the need for observer-dependent collapse, preserves standard quantum mechanics, and makes explicit, falsifiable

predictions. Whether confirmed or constrained, the model sharpens our understanding of quantum behavior and the physical meaning of phase.

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