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Operator-Based Non-local Causal Hidden-variable Quantum Theory for Field Interactions, Interference, and Entanglement without Wave Function Collapse, Self-interference, and Spooky Action

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Abstract

We present a new quantum framework based entirely on Heisenberg's operator formalism, without invoking Schrödinger wavefunctions, superposition, or collapse. Quantum effects arise from discrete, nonlocal but causal momentum and angular momentum transfers between particles and quantized interaction fields. In the double-slit experiment, interference emerges from stochastic, quantized momentum kicks delivered by cavity field modes. In the Stern–Gerlach setup, spin deflection results from quantized angular momentum exchange with a magnetic field gradient, with no need for spinor collapse. This model further explains quantum entanglement via shared nonlocal constraints imposed by quantized field modes, not spooky action or wavefunction entanglement. The framework constitutes a nonlocal hidden variable theory that is deterministic, realist, and consistent with all known quantum interference and entanglement experiments. It reproduces Bell inequality violations through physical field interactions and offers a conceptually clear alternative to conventional quantum mechanics.

Keywords: Quantum Entanglement, Double-Slit Interference, Self-Interference, Wave Function Collapse, Non-Local Hidden Variable, Stern-Grlach Experiment and Bell Inequality

Introduction

Quantum theory, developed in the early 20th century, revolutionized physics by introducing a framework capable of describing atomic and subatomic phenomena. One of its earliest and most puzzling features is wave-particle duality, dramatically demonstrated in the double-slit experiments involving single particles [1,2]. When individual electrons or photons are sent through two slits, they gradually form an interference pattern on a detection screen, even when emitted one at a time [3]. This phenomenon led to the counter-intuitive idea of self-interference, where a particle interferes with itself via a probability wave—a concept formalized by the Schrödinger wavefunction [4,5].

The Copenhagen interpretation, developed by Niels Bohr and Werner Heisenberg, posits that quantum systems are described by a wavefunction that evolves deterministically until a measurement occurs, causing the wavefunction to 'collapse', mysteriously into a definite outcome [6,7]. This interpretation introduces several conceptual problems, including the role of the observer, the lack of a physical collapse mechanism, and the paradox of self-interference. The measurement problem also leads to many-world and parallel universe interpretations [8], and remains one of the central philosophical challenges in quantum mechanics [8].

The Stern–Gerlach experiment revealed the quantization of spin by sending atoms through a nonuniform magnetic field, resulting in discrete deflections rather than a continuous spread [9,10]. The outcome is typically explained by invoking spin superposition and subsequent collapse upon measurement, again relying on the wavefunction formalism. However, this raises questions about the physical reality of spin before measurement.

Quantum entanglement, another key feature of quantum theory, was highlighted in the Einstein-Podolsky-Rosen (EPR) paper which argued that quantum mechanics is incomplete. Entangled particles exhibit correlations that seem to violate local causality, as confirmed by Bell's theorem and subsequent experiments [10,11]. These results rule out local hidden variable theories and appear to support nonlocality—an interpretation Einstein famously called 'spooky action at a distance'.

Alternative interpretations such as Bohemian mechanics propose a nonlocal 'pilot wave' guiding particle trajectories, while the many-worlds interpretation removes collapse entirely by branching the universe at each measurement [12,13]. Despite their ingenuity, these models add complexity and do not resolve the deeper questions of quantum reality.

In conventional quantum mechanics, quantum interference, tunneling, and entanglement are described using wavefunctions and probabilistic amplitude calculations. In our operator-based framework, we replace the wavefunction formalism with quantized mode interactions in barriers or cavities, leading to a more physically intuitive model that does not require wavefunction collapse or nonlocal signaling. In contrast, we propose in this work a different route: an operator-based quantum theory that eliminates the need for wavefunctions, collapse, or superposition. Instead, quantum behavior arises from discrete, nonlocal interactions between particles and quantized fields. This model preserves deterministic evolution and physical realism while remaining consistent with all observed quantum phenomena, including interference, spin measurements, and entanglement. It provides a hidden variable framework with intrinsic nonlocality, offering a compelling alternative to the standard quantum narrative.

In the following sections, we shall first address the double-slit interference, the Stern-Gerlach spin splitting phenomenon, and the quantum entanglement of a polarized pair, based on our operator approach to shed light on quantum reality while avoiding the confusing wavefunction collapse hypothesis and spooky action, which Einstein adamantly opposed.

Operator Approach for Double-Slit Interference of Single Electrons

In this theoretical section, we shall use the operator framework to analyze double-slit interference of single electrons, the Stern-Grlach experiment for single spin-1/2 electrons, and then quantum measurement of an entangled pair and Bell's inequality [14]. According to our previous study [14] based on Heisenberg's quantum operator formalism the Hamiltonian of an electron interacting with a double-slit potential $v(x,y)$ is given by [15]

$$H = \frac{{p_x}^2}{2m} + \frac{{p_y}^2}{2m} + V(x,y)$$

$$V(x,y) = V_0\delta(x)\left(1 - \delta(y - D/2) - \delta(y + D/2)\right) \qquad (1)$$

Where $s(x)$ is the Dirac delta function. According to Heisenberg's mechanics formalism, one has the equation for the most relevant y-component as

$$\frac{d}{dt}p_y = F_y = -\frac{i}{\hbar}[p_y, H] = -\frac{\partial}{\partial y}V(x,y),$$

$$F_y(x,y) = V_0\delta(x)\frac{d}{dy}[\delta(y - D/2) + \delta(y + D/2)]. \qquad (2)$$

One can view the double-slit potential as a field full of quantized cavity modes with the fundamental wavelength as twice of the slit gap, and one has $k_c = \frac{2n_c\pi}{\lambda_c} = \frac{n_c\pi}{D},\ n_c' = 0, \pm1, \pm2, \ldots..$

As an electron passes through either slit, it gains a y-component momentum transfer from the slit potential which is characterized as a bath filled by quantized cavity modes with a quantized field amplitude distribution $\boldsymbol{cos}(n_2\pi D/\lambda_c)$ and a probability of $\boldsymbol{cos^2}(n_2\pi D/\lambda_c)$. This interpretation leads to the same probability distribution of the well-known interference fringes, but with a single dot-like signal image on the detector without the need of wave function collapse and self-interference hypothesized in the Copenhagen interpretation.

Now, we show that our operator approach produces the same interference pattern. As the electron passes either slit it receives a quantized momentum transfer $\Delta p_y = \hbar k_y = n2\pi\hbar/\lambda$, from one of the cavity modes Accordingly, one has

$$\boldsymbol{sin}\theta = \frac{\Delta p_y}{p} = \frac{n_c\hbar 2\pi/\lambda_c}{\hbar 2\pi/\lambda} = \frac{n_c\lambda}{\lambda_c} = \frac{n_c}{N},$$

$$\boldsymbol{sin}\theta = \frac{2n_c V_0\Delta t/\lambda_c}{\hbar 2\pi/\lambda} = \frac{n_c\lambda(v\Delta t/2)}{\lambda_c} = \frac{n_c\lambda}{\lambda_c}, \qquad (3)$$

Where, $N \equiv \lambda_c/\lambda,$ and the minimal uncertainty of $V_0\Delta t/\hbar\pi = \hbar 2\pi v\Delta t/\hbar\pi = 1$ was used. The deflected electron angles due to the electron that involves n-th cavity model passing through the upper beam or the lower beam are given by

$$\boldsymbol{sin}\theta_t = \frac{y_n - D/2}{\sqrt{L^2 + (y - D/2)^2}} = \frac{n_c}{N},\ \boldsymbol{sin}\theta_b = \frac{y_n + D/2}{\sqrt{L^2 + (y + D/2)^2}} = \frac{m_c}{N}. \qquad (4)$$

Because of de Broglie's duality hypothesis, a quantum particle possesses a dual component which can be represented by a complex-value distribution function, and the probability is the squared magnitude. Accordingly, the overall interference intensity from the upper-beam electrons involving the n-th cavity mode and the lower-beam electrons involving the m-th cavity mode is given by

$$I_n \propto cos^2(n_2\pi D/\lambda_c) = cos^2(\pi D\, \boldsymbol{sin}\theta_t/\lambda) = cos^2\left(\frac{\pi D(y + D/2)}{\lambda\sqrt{L^2 + (y + D/2)^2}}\right)$$

$$I_m \propto cos^2\left(\frac{\pi D}{\lambda}\boldsymbol{sin}\theta_m\right) = cos^2(\pi D\, \boldsymbol{sin}\theta_b/\lambda) = cos^2\left(\frac{\pi D(y+D/2)}{\lambda\sqrt{L^2+(y+D/2)^2}}\right), \quad (5A)$$

Where $\boldsymbol{sin}\theta = n_c\lambda/\lambda_c$ was used. Because $N \equiv \lambda_c/\lambda,$, one derive interference intensity from the upper and lower beams as

$$I \propto \sum_n cos^2\left(\frac{\pi D}{\lambda}\frac{y_n - D/2}{\sqrt{L^2+(y_n-D/2)^2}}\right) + \sum_m cos^2\left(\frac{\pi D}{\lambda}\frac{y_m + D/2}{\sqrt{L^2+(y_m+D/2)^2}}\right). \quad (5B)$$

Where y_n or y_m represents the location of the n-th upper-beam or m-th lower-beam electron's dot signal on the screen. After accumulating the intermittent dot signals from arriving single electrons, in the continuum limit of a large N, Eq. (5B) can be reduced to the well-known formula as [16]

$$I(y) \propto cos^2\left(\frac{\pi D(y-D/2)}{\lambda\sqrt{L^2+(y-D/2)^2}}\right) + cos^2\left(\frac{\pi D(y+D/2)}{\lambda\sqrt{L^2+(y+D/2)^2}}\right). \quad (6)$$

The above result is in full agreement with the well-known interference pattern.

Our novel approach to double-slit interference provides a more physical picture of how single electrons, atoms, or C60 molecules of about 0,7 nm in diameter as well as even much larger organic molecules of over 20 nm could result in an interference pattern [17,18]. Our mechanism offers a confusing Copenhagen interpretation.

Operator Approach for the Stern-Grlach Effect

We define the total Hamiltonian as:

$$\hat{H} = \hat{p}_x^2 / 2m + \hat{p}_y^2 / 2m + \hat{p}_z^2 / 2m + \hat{H}_{int} \quad (7)$$

The interaction Hamiltonian models the quantized coupling between the electron spin and magnetic cavity modes localized at x = 0, with a field gradient along y. Inspired by the double-slit quantized field model, we write:

$$\hat{H}_{int} = \Sigma_n\, \hbar\omega_n\, \hat{a}_n^\dagger \hat{a}_n + \Sigma_n\, g_n\, \delta(\hat{x})\, (\hat{a}_n + \hat{a}_n^\dagger)\, \hat{\sigma_z} \quad (8)$$

Where $\hat{a}_n$† and $\hat{a}_n$ are creation/annihilation operators for spin-interaction field modes, ω_n are eigenfrequencies, g_n are coupling constants, σ_z is the Pauli z-operator, and $\delta(\hat{x})$ localizes the interaction at the magnet gap. This setup enables both spatial deflection and spin reorientation.

- **Momentum in y-direction:**

$$d(\hat{p}_y)/dt = -\partial\hat{H}/\partial\hat{y} = 0 \text{ (assuming } g_n \text{ are position-independent)} \quad (9A)$$

The y-momentum change is instead mediated through discrete interaction with the field at x = 0.

- **Spin evolution:**

$$d(\hat{S}_x)/dt = (i/\hbar)[\hat{H}_{int}, S_x] = -(2/\hbar)\, \Sigma_n\, g_n\, \delta(\hat{x})\, (\hat{a}_n + \hat{a}_n^\dagger)\, \hat{S}_y$$

$$d(\hat{S}_y)/dt = (2/\hbar)\, \Sigma_n\, g_n\, \delta(\hat{x})\, (\hat{a}_n + \hat{a}_n^\dagger)\, \hat{S}_x \quad (9B)$$

These describe spin precession about the z-axis, governed by the quantized cavity field interactions. Each magnetic cavity mode n interacts with the spin via $\hat{a}_n$ + $\hat{a}_n$†, analogous to photon exchange in quantum electrodynamics. This results in a discrete momentum transfer in the y-direction, and a quantized torque that reorients the spin vector. Thus, spin deflection and reorientation arise from quantified nonlocal field couplings, without invoking collapse or superposition.

Operator Approach for the Quantum Entanglement of a Polarized Pair

- Recent experiments by Clauser, Aspect, and Zeilinger (2022 Nobel Prize in Physics) demonstrated the violation of Bell's inequality using entangled photon pairs. In standard quantum mechanics, these correlations are interpreted as resulting from wavefunction collapse and instantaneous 'spooky action at a distance.' In contrast, our operator-based framework proposes a radically different interpretation:
- No wavefunction collapse: The polarization states of the entangled photons are determined by quantized cavity

modes during emission, not during measurement.
- No spooky action: The strong correlations are due to a shared quantized polarization mode transmitted through the measuring devices as structured, quantized cavities.
- Causal and deterministic framework: Measurement devices are not classical but actively interact with the polarization modes, inducing quantized angular momentum transfers without invoking nonlocal communication.

$$S = \gamma \cdot | \cos[2(\theta_A - \theta_B)] + \cos[2(\theta_A - \theta_B')] \quad \cos[2(\theta_A' - \theta_B)] \quad \cos[2(\theta_A' - \theta_B')] |$$

The conventional CHSH limit S smaller than or equal to 2 is modified to S smaller than or equal to 2 sqrt(2) λ . For λ greater than 0.707, this model predicts the Bell inequality violation and is consistent with quantum mechanics without invoking wave function collapse.

The 2022 Nobel Prize experiments demonstrated strong correlations in entangled photon pairs, interpreted through wavefunction collapse. However, our model provides a new interpretation that aligns with these experimental findings while rejecting collapse and nonlocal signaling.

- **Quantized Mode Transfer:** In our framework, polarizers act as quantized cavities, actively mediating polarization transfer through discrete angular momentum exchanges.
- **No Wavefunction Collapse:** The strong correlations are established by quantized mode interactions, not by wavefunction collapse. The measured polarization state is not 'instantaneously set' but rather determined by the interaction with the quantized cavity.
- **No Spooky Action:** The apparent 'instantaneous correlation' is not due to faster-than-light communication but to pre-existing shared quantized modes that are synchronized during emission and maintained through quantized interactions.

Discussion and Implications

Our operator-based framework offers a significant departure from conventional quantum mechanics by rejecting the wavefunction collapse interpretation and instead treating measurement devices as quantum-active structures capable of quantized polarization and momentum transfer. This perspective aligns with recent experimental results in quantum entanglement, particularly the 2022 Nobel Prize experiments by Clauser, Aspect, and Zeilinger, which demonstrated strong quantum correlations in polarization measurements. While traditional interpretations attribute these correlations to wavefunction collapse and nonlocal 'spooky action,' our model provides a more physically intuitive explanation based on quantized polarization modes interacting with structured cavities.

By incorporating a decoherence factor, our revised Bell inequality formulation bridges the gap between deterministic polarization transfer and stochastic measurement outcomes, allowing for Bell violations without invoking nonlocality or instantaneous communication. This approach not only aligns with Einstein's vision of a causal, realistic quantum theory but also preserves the core experimental findings of entanglement without requiring superluminal signaling.

The proposed operator-based framework reinterprets quantum phenomena, including tunneling, double-slit interference, and polarization entanglement, through the lens of quantized mode transfer without the need for wavefunction collapse or nonlocal action. By treating measuring devices as structured quantum cavities that mediate discrete angular momentum transfers, our model provides a unified theoretical approach that is both physically intuitive and experimentally consistent with recent entanglement tests. The introduction of the decoherence factor \(\gamma \) allows us to quantitatively account for mode interaction losses, establishing a clear boundary for observing quantum correlations in entanglement experiments. This reinterpretation not only challenges the conventional Copenhagen interpretation but also paves the way for a more deterministic, operator-based quantum field theory that preserves locality and causality.

Summary and Outlook

This work presents a fundamentally new approach to quantum mechanics grounded in Heisenberg's operator formalism. By removing reliance on wavefunctions, superposition, and collapse, we construct a physically intuitive, mathematically consistent framework in which quantum effects arise from quantized, nonlocal interactions with structured fields. This paradigm successfully reproduces classical results of quantum theory—including interference, spin quantization, and entanglement—without invoking paradoxes or observer-centric concepts.

Our model supports a hidden variable interpretation with built-in nonlocality due to quantized field dynamics, offering a deterministic and realist account of quantum behavior. It aligns with Einstein's critique of the incompleteness of quantum mechanics while remaining fully consistent with all observed experimental data, including Bell-inequality violations. The rejection of wavefunction collapse and self-interference eliminates confusion and refocuses the foundations of quantum theory on physical interactions and measurable operator dynamics.

Looking ahead, this framework can be expanded to encompass relativistic quantum systems, quantum information protocols, and many-body entangled states. It invites re-examination of longstanding quantum paradoxes through a new lens and may contribute to bridging the gap between quantum and classical realities. Furthermore, it opens the possibility of new experimental designs aimed at validating predictions unique to operator-based dynamics with quantized field couplings.

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