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Reconstructing Quantum Mechanics: A Vortex-Based Replacement for Schrödinger's Equation

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Abstract

This article proposes a deterministic and geometrically grounded reformulation of quantum mechanics based on vortex dynamics in a structured, superfluid-like vacuum. Modeling the electron as a self-sustaining irrotational vortex with both internal rotation and external translation, the framework derives fundamental quantum phenomena—including de Broglie wavelength, Compton wavelength, spin, and quantization—directly from physical principles of motion and vacuum geometry. A generalized wave function is introduced, embedding both translational and rotational phase components, leading to a modified Schrödinger-like equation that naturally incorporates internal angular momentum. Interference, tunneling, and entanglement are reinterpreted as emergent behaviors of coherent vortex trajectories, eliminating the need for wavefunction collapse or intrinsic randomness. The Born rule is shown to arise from deterministic mechanisms such as phase averaging, internal oscillations, and ergodic dynamics. This vortex model aligns with classical, quantum, and relativistic principles, resolves key interpretational paradoxes, and offers a unified, causal framework for understanding quantum phenomena as structured motion within a physically real vacuum.

Keywords

Vortex Wave Function, Deterministic Quantum Model, Electron Spin, De Broglie Wavelength, Compton Wavelength, Quantum Interference, Schrödinger Equation, Wave-Particle Duality, Geometric Quantization, Superfluid Vacuum, Quantum Coherence

1. Introduction

The duality of matter, exhibiting both particle-like and wave-like behavior, has long stood as one of the most mysterious and foundational principles in modern physics. Since Louis de Broglie's 1924 hypothesis that each particle of matter is associated with a wavelength, $\lambda = h/p$, experiments such as electron diffraction and the double-slit test have confirmed the wave nature of matter. Building on this insight, Erwin Schrödinger developed wave mechanics and introduced the concept of a wave function ψ, whose squared modulus $|\psi|^2$ was reinterpreted by Max Born as a probability density for finding a particle in space and time.

While quantum mechanics has achieved extraordinary predictive success, the physical interpretation of the wave function remains incomplete. The standard model treats the electron as a point particle with intrinsic properties such as charge, mass, and spin, yet it fails to provide a mechanistic or structural explanation for these features. The probabilistic framework—effective in calculating outcomes—offers little insight into the physical origin of the electron's wave behavior, the Lorentz factor in relativistic dynamics, or the intrinsic properties such as spin and charge.

In recent years, the author has proposed a series of theories aimed at providing a more tangible understanding of the electron's characteristics. In "Electron Shape and Structure: A New Vortex Theory" [1], the electron is introduced as a frictionless vortex composed of condensed vacuum, generated from massless virtual photons acquiring mass through vortex motion at the speed of light. This model offers explanations for the electron's mass, volume, and density using classical hydrodynamic principles. Building upon this, "A New Theory on Electron Wave-Particle Duality" [2] uses the vortex model to describe the electron's motion as a three-dimensional helix resulting from the combination of internal rotation and external translation. This motion provides a physical foundation for the de Broglie wavelength and offers insight into the geometric origin of the Lorentz factor. The framework is further expanded in "A New Theory for the Essence and Nature of Electron Charge" [3], which redefines electric charge through hydrodynamic symmetry, and in "A New Theory for the Essence and Origin of Electron Spin" [4], which links intrinsic angular momentum to the structure of the vortex itself.

Although these works offer substantial advances in describing the electron's properties, the probabilistic interpretation of the wave function, as formulated by Schrödinger, remains central to quantum mechanics. Integrating the vortex model with this framework could bridge the gap between classical and quantum descriptions, offering a more coherent and physically grounded picture of quantum behavior.

In this article, these foundational theories are synthesized to present a unified, classical model of the electron as a self-sustaining vortex structure in space. The model posits that the electron possesses both internal rotational motion—responsible for the Compton wavelength—and external translational motion—associated with the de Broglie wavelength—yielding a helical trajectory in spacetime. It is shown that the Lorentz factor emerges naturally from a geometric decomposition of the total motion into orthogonal internal and external components.

Contrary to the probabilistic interpretation, the electron's wave-like behavior in this model arises as a direct manifestation of its physical motion through space. The Schrödinger wave function is reinterpreted as a projection of the electron's three-dimensional vortex helix, where interference, tunneling, and quantization stem from real geometry and motion rather than abstract uncertainty. The goal of this work is to mathematically derive angular momentum, wavelength, and energy relations from first principles, and to demonstrate that quantum-like behavior is an emergent feature of deterministic vortex dynamics. The Compton wavelength reflects the internal rotation cycle, while the de Broglie wavelength corresponds to the pitch of the helical path. This framework may illuminate quantum phenomena such as coherence, entanglement, and even superconductivity, and could provide a bridge toward unifying classical mechanics with quantum field theory.

2. Historical Foundations and the Limitations of Classical and Standard Quantum Approaches

2.1. The Crisis Leading to Schrödinger's Equation

Since the early 20th century, the attempt to reconcile the wave-like and particle-like behavior of the electron led to profound shifts in theoretical physics. The classical formalism of mechanics, based on Newtonian trajectories or even relativistic corrections, proved incapable of accounting for phenomena like electron diffraction, interference, and atomic energy quantization.

Following the 1924 proposal by Louis de Broglie [5], which postulated that particles such as electrons possess a wavelength inversely proportional to their momentum ($\lambda = h/p$), experimental confirmations soon followed—most notably electron diffraction patterns that mimicked those of light waves [6].

This profound revelation introduced the notion that matter could not be fully described by trajectories alone and that wave dynamics had to be incorporated into the theory of motion.

However, incorporating wave behavior into the classical framework proved challenging. The electromagnetic wave equations, which describe light propagation through space, could not be directly applied to matter waves like those of the electron. Electrons are localized, charged, and massive, and their wave-like behavior could not be captured by Maxwell's equations or the classical wave equation. Attempts to use these frameworks led to contradictions: wave equations predict dispersion and infinite spreading, while electrons remain localized and discrete when measured.

The difficulty became more pronounced when trying to describe stable atomic structures. According to classical electrodynamics, an electron orbiting a nucleus would emit radiation and spiral inward due to energy loss, contradicting the observed stability of atoms. Moreover, classical mechanics could not explain the discrete energy levels of the hydrogen atom.

This prompted Erwin Schrödinger, in 1926, to formulate a new wave equation [7]—now known as the Schrödinger equation—that treats the electron not as a particle moving on a definite path, but as a distributed wavefunction $\psi(x, t)$. The squared modulus $|\psi|^2$, interpreted by Max Born [8], provided a probabilistic description of the likelihood of finding the electron at a given location and time. Schrödinger's approach successfully reproduced the quantized energy levels of hydrogen and became the cornerstone of quantum mechanics.

While immensely successful in practice, the Schrödinger equation introduced a new kind of formalism: it abandoned determinism in favor of statistical interpretation, disconnected the wavefunction from physical structure, and placed measurement—and the observer—at the heart of the theory. The equation describes how the wavefunction evolves, but not what it physically represents. The electron, once seen as a definite entity with a path and a structure, became a mathematical abstraction governed by probability amplitudes.

In this work, we revisit the origin of the Schrödinger equation not to dispute its empirical validity, but to offer a new perspective grounded in physical geometry and deterministic motion. We propose that the underlying need for a probabilistic wavefunction arises from a limited view of the electron as a point-like particle. If instead we consider the electron as a self-sustained vortex—a dynamic, spatially extended structure with both internal rotation and external translation—then the wave-like properties naturally emerge from the geometry of its motion.

In this vortex-based model, the internal rotation of the electron defines a Compton-scale circulation, while its external motion corresponds to the de Broglie wavelength. The resulting trajectory is a three-dimensional helix. From this structure, quantization, interference, tunneling, and wave-like phenomena arise not from uncertainty, but from deterministic, structured motion in space-time. The need for Schrödinger's probabilistic interpretation is thus reframed: not as a fundamental aspect of nature, but as an artifact of incomplete modeling.

Our aim is to reconstruct quantum mechanics from first principles using this vortex foundation, replacing abstract wavefunctions with real, observable, and mathematically consistent vortex motion that preserves all experimentally confirmed predictions while restoring physical intuition, determinism, and continuity to the theory.

2.2. The Limitations of Classical Wave Functions for Describing Electrons

In classical physics, wave phenomena are described by continuous, deterministic functions that evolve smoothly in space and time, representing tangible physical oscillations. For instance, sound waves in a medium like air are longitudinal mechanical waves, where the wave function describes the displacement of particles. Similarly, electromagnetic waves, such as light, are transverse oscillations of electric and magnetic fields, governed by Maxwell's equations. These classical wave functions are well-understood and experimentally validated. However, attempts to directly apply these classical wave concepts to describe particles like electrons encountered insurmountable difficulties.

Firstly, classical waves typically propagate through a medium (e.g., air for sound) or represent disturbances in a field (e.g., the electromagnetic field for light). For the electron, no such obvious medium or underlying field was apparent. The question of what was "oscillating" to constitute the electron's wave nature remained unanswered.

Secondly, classical waves distribute their energy continuously across the wavefront as they propagate. In contrast, electrons, despite exhibiting wave-like interference, are always detected as localized, point-like particles, depositing their entire energy at a single location. This particulate nature upon detection was incompatible with the continuous energy distribution characteristic of classical waves.

Thirdly, the phenomenon of interference, as observed in the double-slit experiment, posed a conceptual challenge. While classical waves interfere by the superposition of amplitudes from different paths, electrons were observed to build up interference patterns even when passing through the apparatus one at a time. This suggested that the electron's wave function described a probability amplitude for a single particle rather than a classical physical wave distributed across multiple paths simultaneously.

Fourthly, the concept of wave function collapse upon measurement, a cornerstone of the Copenhagen interpretation, has no analogue in classical wave theory. Classical waves can be superposed and their components can be measured without an abrupt, discontinuous change in their state. For electrons, however, the act of measurement appeared to instantaneously collapse the wave function from a superposition of possibilities to a single, definite state. Finally, classical waves can possess a continuous spectrum of energies, typically dependent on their amplitude and frequency. Electrons in bound systems, such as atoms, however, are restricted to discrete, quantized energy levels, as evidenced by atomic spectra. This fundamental incompatibility between the continuous energy spectrum of classical waves and the quantized energy levels of electrons could not be reconciled within a purely classical framework.

In summary, the direct application of classical wave function concepts to electrons failed to account for their particulate nature upon detection, the probabilistic nature of their interference, the phenomenon of wave function collapse, and the quantization of their energy levels. This necessitated a radical departure from classical thinking, leading to the development of quantum mechanics, wherein the electron's wave function is interpreted not as a physical wave in the classical sense, but as a mathematical construct encoding probability amplitudes.

2.3. Failure of Classical Wave Theory to Describe the Electron (Mathematical Argument)

Following de Broglie's hypothesis that particles such as electrons exhibit wave-like properties, initial attempts were made to describe their behavior using the classical wave equation. This equation, derived from mechanical and electromagnetic wave theory, typically takes the form:

$$\frac{\partial^2 \psi}{\partial t^2} = c^2 \nabla^2 \psi \tag{2.3.1}$$

where ψ represents a field quantity, and c is the propagation speed of the wave (e.g., the speed of light for electromagnetic fields). This second-order partial differential equation accurately describes phenomena like sound waves in air and electromagnetic waves in vacuum, assuming linear dispersion and constant propagation speed [9].

To adapt this equation for matter waves, one might insert a plane wave solution of the form:

$$\psi(r,t) = A\cos(k \cdot r - \omega t) \tag{2.3.2}$$

where A is the amplitude, r is the position vector, t is time, k is the wave vector ($|k| = 2\pi/\lambda$), and ω is the angular frequency ($\omega = 2\pi f$). Substituting this into the classical wave Equation (2.3.1) yields the dispersion relation:

$$\omega = c|k| \tag{2.3.3}$$

According to de Broglie, the wave properties of a particle such as an electron are connected to its momentum and energy through the relations:

$$p = \hbar k, \quad E = \hbar\omega \quad [10] \tag{2.3.4}$$

Combining these relations with the dispersion relation from the classical wave equation ($\omega = c|k|$) leads to:

$$E = pc \tag{2.3.5}$$

This fundamental discrepancy demonstrates that the classical wave equation, in its standard form, cannot adequately describe the wave properties of massive particles like electrons. It fails to incorporate the correct energy-momentum relationship and thus cannot account for their dynamics. This failure underscored the necessity for a new theoretical framework, which eventually emerged in the form of Schrödinger's wave mechanics and, later, relativistic quantum mechanics.

2.4. The Schrödinger Equation: Mathematical Foundations and Interpretational Challenges

The Schrödinger equation stands as a seminal achievement in 20th-century theoretical physics. Formulated by Erwin Schrödinger in 1925-1926, it provides the fundamental mathematical framework for describing the behavior of quantum systems [11].

The time-dependent Schrödinger equation governs the evolution of a quantum state $\Psi(r,t)$ over time:

$$i\hbar \frac{\partial \Psi(r,t)}{\partial t} = \hat{H}\Psi(r,t) \tag{2.4.1}$$

(a complex-valued function of position r and time t), $\hbar$ is the reduced Planck constant ($h/2\pi$), i is the imaginary unit, and $\hat{H}$ is the Hamiltonian operator, representing the total energy of the system. For a single non-relativistic particle of mass m moving in a potential $V(r)$, the Hamiltonian is:

$$\hat{H} = -\frac{\hbar^2}{2m}\nabla^2 + V(r) \tag{2.4.2}$$

If the Hamiltonian is time-independent, the wave function can be separated as $\Psi(r,t) = \psi(r)e^{-iEt/\hbar}$, leading to the time-independent Schrödinger equation:

$$\hat{H}\psi(r) = E\psi(r) \tag{2.4.3}$$

Or, more explicitly:

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(r)\right]\psi(r) = E\psi(r) \tag{2.4.4}$$

where E represents the energy of the system, and $\psi(r)$ are the corresponding energy eigenstates or stationary states.

The wave function Ψ itself is not directly observable. According to the Born rule [12], $|\Psi(r,t)|^2$ represents the probability density of finding the particle at position r at time t. This probabilistic interpretation signifies a fundamental departure from classical determinism. The wave function must be continuous, normalizable ($\int|\Psi|^2 \mathrm{d}V = 1$), and satisfy system-specific boundary conditions.

Time-Independent Schrödinger Equation

If the potential $V(r)$ is not time-dependent, the wave function can be separated into spatial and temporal components:

$$\psi(r,t) = \psi(r)e^{-iEt/\hbar} \tag{2.4.1.1}$$

Substituting into the time-dependent equation yields the time-independent Schrödinger equation:

$$\hat{H}\psi(r) = E\psi(r) \tag{2.4.1.2}$$

or explicitly:

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(r)\right]\psi(r) = E\psi(r) \tag{2.4.1.3}$$

here, E represents the energy eigenvalues, and $\psi(r)$ are the corresponding stationary states.

Although the Schrödinger equation yields precise predictions for quantum systems, its interpretation poses significant philosophical challenges. The wave function $\Psi(r,t)$ is not directly observable; its modulus squared $|\Psi|^2$ gives the probability density for locating a particle in space and time, according to the Born rule.

Mathematically, the Schrödinger equation exhibits two key properties:

linearity (allowing for superposition of states) and unitarity (preserving total probability over time).

A significant interpretational challenge arises from the measurement problem: while the Schrödinger equation describes a deterministic evolution of Ψ, measurement outcomes are probabilistic. This leads to the concept of wave function collapse, where, upon measurement, Ψ instantaneously transitions to a specific eigenstate—a process not described by the Schrödinger equation itself.

Furthermore, Heisenberg's uncertainty principle imposes fundamental limits on the simultaneous precision with which complementary variables (e.g., position and momentum, $\Delta x \Delta p \geq \hbar/2$) can be known. This inherent uncertainty reinforces the probabilistic nature of quantum mechanics. The Copenhagen interpretation, historically dominant, accepts these features as intrinsic aspects of nature, viewing the wave function as representing knowledge about the system rather than its objective physical reality.

These interpretational difficulties have motivated the search for alternative formulations, including deterministic approaches.

3. The Philosophical Tension and the Rise of Deterministic Reformulations

The probabilistic nature of quantum mechanics poses significant philosophical challenges to our understanding of physical reality:

1) **Determinism vs. Indeterminism**: Quantum mechanics appears to contradict the Laplacian view that the universe evolves deterministically according to precise laws [12] [13].

2) **Realism**: The question of whether quantum objects possess definite properties before measurement has led to debates about the nature of physical reality [14] [15].

3) **Locality**: Quantum entanglement suggests that measurements on one particle can instantaneously affect another particle, regardless of the distance separating them, challenging our notions of locality [16] [17].

4) **Causality**: The apparent randomness in quantum measurements raises questions about causality at the fundamental level [18] [19].

5) **Completeness**: Einstein and others questioned whether quantum mechanics provides a complete description of physical reality, famously arguing that 'God does not play dice [20].

These philosophical challenges, coupled with the unresolved measurement problem and the difficulty of reconciling quantum theory with general relativity, have motivated a continuous search for alternative interpretations and reformulations of quantum mechanics. A significant strand of this research has focused on developing deterministic theories that aim to preserve the empirical successes of quantum mechanics while restoring a more classical understanding of causality, realism, and determinism. The aspiration is to formulate a theory that is not only empirically adequate but also conceptually coherent, potentially resolving the paradoxes associated with the standard interpretation and offering a more unified description of physical phenomena across different scales.

3.1. Overview of Deterministic Reformulations (e.g., Pilot Wave Theory)

Among the various proposals aimed at restoring determinism to quantum physics, the pilot-wave theory, also known as Bohmian mechanics or the de Broglie-

Bohm theory, stands as one of the most developed and conceptually distinct alternatives. First proposed by Louis de Broglie in 1927 [21] and later independently rediscovered and extended by David Bohm in 1952 [22], this theory posits that quantum particles possess definite positions at all times and follow deterministic trajectories. These trajectories are guided by a wave function, which itself evolves according to the standard Schrödinger equation.

In this framework, both the particle and the wave are considered ontologically real. The wave function does not merely describe the probability of finding a particle but actively influences its motion through a guiding equation. For a non-relativistic particle, the velocity is determined by the gradient of the phase of the wave function. A key feature of Bohmian mechanics is the emergence of a "quantum potential", an additional term in the equations of motion that depends on the curvature of the amplitude of the wave function. This quantum potential is responsible for characteristically quantum phenomena, such as interference in the double-slit experiment and quantum tunneling. It is non-local, meaning it can depend on the configuration of the wave function across all space, thus naturally accommodating quantum entanglement without invoking wave function collapse. Bohmian mechanics is empirically equivalent to standard quantum mechanics; it reproduces all of its statistical predictions, provided that the initial distribution of particle positions is assumed to conform to the Born rule (*i.e.*, $\rho(x,0)=|\Psi(x,0)|^2$), an assumption known as the "quantum equilibrium hypothesis". While it resolves the measurement problem by denying that measurements are fundamentally different from other physical processes (there is no collapse), it introduces its own set of conceptual challenges, including the nature of the wave function in a multi-particle system (which resides in configuration space) and the implications of its inherent non-locality in a relativistic context. Despite these challenges, pilot-wave theory demonstrates that a deterministic underpinning for quantum phenomena is mathematically consistent and empirically viable, thereby challenging the notion that indeterminism is an unavoidable feature of the quantum world. It serves as a prominent example of efforts to provide a more complete and potentially more intuitive understanding of quantum reality.

3.2. Comparison with the Bohmian (Pilot-Wave) Interpretation

While both the vortex-based model and Bohmian mechanics seek to restore determinism and realism to quantum theory, they differ fundamentally in ontology, mathematical formalism, and physical interpretation.

3.2.1. Ontology and Physical Structure

In Bohmian mechanics, particles are point-like objects guided by a pilot wave (the wave function), which evolves according to the Schrödinger equation. The wave function exists in a high-dimensional configuration space and exerts a nonlocal influence on particle trajectories via the quantum potential.

In contrast, the vortex model proposes that the electron is not a point particle but a self-sustaining, irrotational vortex in a structured, superfluid-like vacuum. Its internal geometry—including circulation, rotational velocity, and phase structure—defines its quantum properties. The wave function in this model is not an abstract guiding field but a direct expression of the electron's real, three-dimensional helical motion in physical space.

3.2.2. Wave Function Interpretation

Bohmian mechanics retains the standard Schrödinger wave function and interprets it as a real entity that guides particle trajectories through a quantum potential. This potential introduces nonlocal interactions and is responsible for interference and entanglement effects.

The vortex model, by contrast, derives a new wave function from first principles of vortex motion. This function incorporates both translational (de Broglie-scale) and rotational (Compton-scale) phase components, resulting in a modified Schrödinger-like equation. Interference, spin, and tunneling emerge not from an external guiding wave but from the geometry and dynamics of the vortex itself.

3.2.3. Role of the Quantum Potential

In Bohmian mechanics, the quantum potential plays a central and somewhat abstract role. It governs the acceleration of particles based on the curvature of the wave function and is responsible for the non-classical aspects of motion.

The vortex model eliminates the need for a quantum potential. Instead, the internal rotational dynamics of the vortex and its interaction with vacuum elasticity generate the observed quantum behaviors. Quantization arises naturally from geometric constraints and boundary conditions of vortex stability.

3.2.4. Nonlocality and Entanglement

Both models accommodate quantum nonlocality, but through different mechanisms. Bohmian mechanics invokes instantaneous action-at-a-distance through the configuration space wave function. This approach, while mathematically consistent, raises tension with relativistic causality.

In the vortex model, nonlocal correlations arise from phase coherence and conservation of angular momentum across spatially separated but dynamically entangled vortex systems. The vacuum medium acts as a continuous field supporting instantaneous phase alignment without requiring superluminal signaling, thus offering a more physically intuitive account of entanglement.

3.2.5. Probability and the Born Rule

Bohmian mechanics assumes the Born rule as a postulate via the quantum equilibrium hypothesis. In contrast, the vortex model offers a pathway to derive the Born rule from deterministic principles. Statistical distributions of detection events arise from ensemble phase averaging, chaotic core oscillations, and ergodic internal dynamics—making the Born rule an emergent, not axiomatic, property (see Table 1).

Table 1. Summary comparison.

Aspect	Bohmian Mechanics	Vortex Model
Particle Nature	Point particle	Vortex structure in physical space
Wave Function	Schrödinger wave in configuration space	Structured wave from internal motion
Nonlocality	Via quantum potential	Via phase-locked vortex dynamics
Spin Interpretation	Postulated intrinsic property	Geometric origin from internal rotation
Quantum Potential	Central to particle dynamics	Not needed; replaced by vortex geometry
Born Rule	Postulated (quantum equilibrium)	Emergent from internal deterministic dynamics

In conclusion, the vortex model complements and advances the deterministic agenda initiated by Bohmian mechanics. While Bohm reintroduced causality and realism, the vortex framework grounds these principles in a physically visualizable and mathematically unified theory that may bridge quantum mechanics, classical fields, and relativity in a single coherent model.

4. Physical Vacuum as a Quantum Superfluid

This vortex-based theory naturally implies a vacuum with physical properties: density, elasticity, and compressibility [23].

The vacuum acts as the medium through which energy is condensed into mass. Virtual photons rotating in vortex motion acquire real mass, and their quantized circulation is what gives rise to measurable quantities such as electric charge and spin.

This theoretical shift—seeing the electron as a structure in a continuous medium—provides a physically visualizable and mathematically consistent alternative to the abstract probabilistic frameworks. It also lays the groundwork for integrating the vortex model into larger hydrodynamic quantum theories.

In the following chapter, we extend this interpretation by integrating the electron vortex theory with the quantum hydrodynamic model of the vacuum proposed by Sbitnev. His generalized Navier-Stokes equation, derived for a superfluid vacuum, confirms the possibility of stable vortex structures and supports the theoretical underpinnings of the vortex electron model presented here.

5. Electron as a Vortex Structure in Superfluid Vacuum

The conventional portrayal of the electron in the Standard Model is that of a point-like particle, devoid of any internal structure or shape. Despite this abstraction, the electron exhibits several features that suggest underlying structure: spin, magnetic moment, rest mass, and interaction with quantum vacuum fluctuations. The inability of the Standard Model to offer a visualizable explanation for these properties has prompted the development of alternative theoretical frameworks.

In the proposed vortex model introduced by the author [1], the electron is conceived not as a mathematical point, but as a dynamic, self-organizing vortex structure formed in a superfluid vacuum. The vacuum itself is understood as a quantum superfluid medium, permeated by virtual particle-antiparticle pairs, capable of sustaining quantized vortical motion.

5.1. The Electron as a Self-Sustaining Vortex

In this model, the electron comprises two essential motions:

1) Internal rotation at the speed of light along a circular path with a radius equal to the reduced Compton wavelength, ($\bar{\lambda}_C = \hbar / mc$, where $\hbar$ is the reduced Planck constant and m is the electron mass).

2) External translational motion with velocity, producing a de Broglie wavelength, ($\lambda_{dB} = h/p$, where p is the electron's momentum).

These motions generate a helical trajectory in spacetime, unifying the wave-particle duality into a single geometric configuration. The vortex is considered irrotational at the core, with streamlines forming concentric spirals. The superfluid medium ensures frictionless circulation, stabilizing the vortex through vacuum elasticity and conserving angular momentum.

5.2. Mass, Spin, and Charge from Hydrodynamics

By applying classical hydrodynamics to the vortex in a compressible, elastic vacuum, key physical quantities are derived:

- **Mass** is proportional to the vacuum density times the volume swept by the vortex.
- **Spin** arises from the intrinsic angular momentum, matching quantum predictions.
- **Charge** is interpreted as a result of vortex-induced vacuum flow, related to the volume flow rate and vacuum permittivity.

This model reproduces observed quantities such as the Compton wavelength, de Broglie wavelength, Planck constant, and even predicts the electron's minimum time cycle and density. It proposes that the vortex core acts as a site of vacuum breakdown, forming a field-less void where centrifugal and centripetal forces balance.

5.3. Spin Angular Momentum in the Vortex Model

A longstanding mystery in quantum physics is the origin and meaning of electron spin. While standard quantum mechanics attributes spin to an intrinsic angular momentum without spatial rotation, the vortex model offers a classical, geometric explanation. In this framework, spin arises naturally from the internal rotational dynamics of the vortex.

This interpretation was elaborated in the author's previous work, "*A New Theory for the Essence and Origin of Electron Spin*" [4], where spin is shown to emerge from the differential rotational dynamics between the vortex core and its boundaries. The electron is modeled as a frictionless irrotational vortex in a superfluid vacuum, whose angular momentum is conserved and equivalent to Planck's constant.

The electron vortex rotates internally at the speed of light, and this motion is constrained by the reduced Compton wavelength $\lambda_c = \frac{\hbar}{mc}$ giving a vortex radius $r = \frac{\lambda_c}{2\pi} = \frac{\hbar}{mc}$.

The angular momentum (spin) then becomes:

$$L_z = I\omega_{rot} = \left(mr^2\right)\left(c/r\right) = mcr = mc\left(\hbar/mc\right) = \hbar$$

This total angular momentum matches the quantum prediction. However, quantum mechanics measures only the projection of spin along an axis, yielding:

$$S_z = \pm\hbar/2$$

The vortex model explains this discrepancy. During the formation of the vortex, a differential rotation arises between the vortex core and its boundaries. The vortex core completes two full rotations (2 × 360˚) for every single rotation (360˚) at the boundary. This ratio manifests as the spin-1/2 behavior: the vortex must rotate 720 degrees to return to its original configuration.

Thus, the spin quantum number 1/2 reflects this intrinsic geometric lag in vortex rotation—a physical, measurable consequence of substructure rather than an abstract property. The quantization of spin follows from boundary conditions of stable vortex formation in a frictionless medium.

5.4. Wave-Particle Duality Reinterpreted

According to the Standard Model, the electron is considered structureless. Yet, it exhibits angular momentum (spin), magnetic moment, and apparent internal oscillation—features typically associated with extended objects. Dirac's equation in 1928 indicated the presence of internal motion at the speed of light, while experimental evidence suggested slight asymmetries in the electron's charge distribution.

In the vortex model, the electron is a frictionless, irrotational vortex formed from vacuum condensation. The vortex has a circular core where the speed of rotation at every point is the speed of light, and the circulation $\Gamma_e = 2\pi r_e c$ is constant. The momentum associated with this circulation yields:

$$\Gamma_e = 2\pi r_e c,\ h = \Gamma_e m_e,\ r_e = h/2\pi m_e c \tag{5.4.1}$$

This provides a physical derivation for the Compton wavelength $\lambda_C = 2\pi r = h/mc$. The wave-like properties of the electron are tied to this structure:

- One full rotation of the vortex corresponds to the Compton wavelength.
- The pitch of the helical path taken by the traveling electron corresponds to the

de Broglie wavelength [2].

The rotational frequency $f = c/2\pi r$ matches the frequency derived from Planck's relation $E = hf$, confirming the equivalence.

This model bridges the gap between classical mechanics and quantum theory, providing real geometry behind wave-particle duality. The de Broglie wavelength emerges from the translational motion, while the Compton wavelength arises from the internal rotation.

6. Hydrodynamics of the Physical Vacuum: Integrating Vortex Dynamics into Quantum Theory

To further validate and extend the electron vortex model, we turn to the hydrodynamic formulation of quantum mechanics—specifically the treatment of the physical vacuum as a superfluid medium. This perspective, championed by V. I. Sbitnev [24], models the quantum vacuum as a compressible, dynamic fluid populated by virtual particles. Within this framework, stable vortex structures emerge as natural solutions of modified Navier-Stokes equations, reinforcing the physical plausibility of representing the electron as a coherent vortex configuration in vacuum.

The modified Navier-Stokes equation tailored for a quantum superfluid vacuum populated by virtual particle-antiparticle pairs. This vacuum is governed by:

$$m\left(\frac{\partial v}{\partial t}+\left(v\cdot\nabla\right)v\right)=-\nabla Q+\frac{F}{N}+\nu\left(t\right)\nabla^{2}\left(mv\right), \tag{6.1}$$

accompanied by the continuity equation:

$$\frac{\partial\rho}{\partial t}+\nabla\cdot\left(\rho v\right)=0, \tag{6.2}$$

Here, $v = v_S + v_R$ includes both irrotational and solenoidal components, Q is the quantum potential, and $\nu(t)$ is a fluctuating viscosity that supports persistent vortex structures. The vacuum behaves as a quantum fluid, and vortex solutions such as:

$$\omega\left(r,t\right)=\frac{\Gamma}{4\Sigma\left(t\right)}\exp\left(-\frac{r^{2}}{4\Sigma\left(t\right)}\right), \tag{6.3}$$

$$v\left(r,t\right)=\frac{\Gamma}{2r}\left(1-\exp\left(-\frac{r^{2}}{4\Sigma\left(t\right)}\right)\right), \tag{6.4}$$

describe stable vortex cores due to the vacuum's zero-point energy dynamics.

Integration of Sbitnev's Hydrodynamics with the Vortex Model

Building on Sbitnev's quantum hydrodynamic framework, we incorporate a time-dependent oscillation of the vortex core radius to model fluctuations arising from vacuum elasticity and intrinsic quantum spinor dynamics. This dynamic trembling of the vortex core—interpreted as a localized manifestation of Zitterbewegung—can be described by:

$$r_{core}(t) \approx 2\sqrt{\frac{a_0 \nu}{\Omega} \cdot \frac{\sin(\Omega t) + n}{\Omega}} \tag{6.1.1}$$

where:

- a_0 is the characteristic initial radius of the vortex core,
- ν is a frequency linked to vacuum density or elasticity,
- Ω is the primary oscillation frequency of the trembling motion,
- n is an integer or small perturbation parameter accounting for fluctuation symmetry.

This time-dependent radial modulation is consistent with Sbitnev's generalized vorticity model, where quantum pressure and vacuum tension drive nonlocal dynamics. In our vortex framework, it reinforces the interpretation of the electron as a coherent structure in a superfluid-like vacuum background, with internal rotational structure superimposed on a de Broglie-guided translational path.

To incorporate these dynamics into a wave equation, we apply the appropriate energy operators to the structured wavefunction $\psi(r,\theta,t)$:

- Translational kinetic energy: $T_{trans} = -\frac{\hbar^2 \partial^2}{2m\partial z^2}$ (6.1.2)
- Rotational kinetic energy: $T_{rot} = -\frac{\hbar^2 \partial^2}{2I\partial \theta^2}$ (6.1.3)

where $I = mr^2$ is the moment of inertia of the vortex core.

Thus, the full vortex evolution equation becomes:

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2 \partial^2 \psi}{2m\partial z^2} - \frac{\hbar^2 \partial^2 \psi}{2I\partial \theta^2} + V(r,t)\psi \, , \tag{6.1.4}$$

where $V(r,t)$ may represent a potential term (external or self-consistent) depending on the vortex interaction with surrounding fields.

This formulation captures:

- The helical translational motion governed by the de Broglie wavelength,
- The internal vortex rotation governed by the Compton scale,
- The modulation of vortex core radius from vacuum-induced fluctuations.

It bridges quantum field principles with hydrodynamic realism, opening a path for a physically grounded replacement of the Schrödinger equation rooted in vortex dynamics and superfluid vacuum theory.

7. The Vortex Wave Function

To bridge the gap between classical determinism and quantum mechanics, the vortex model of the electron introduces a physically meaningful wave function. Unlike the abstract probabilistic interpretation of standard quantum theory, this model treats the electron as a structured, self-contained vortex—composed of condensed energy rotating and translating through a superfluid-like vacuum.

To mathematically describe this structured electron, the following vortex wave function is proposed:

$$\psi(r,t) = A \cdot \exp\left[i\left(\frac{2\pi z}{\lambda_{dB}} - \omega t + \frac{2\pi\theta}{\lambda_C}\right)\right] \tag{7.1}$$

where:

- $r = (x, y, z)$ is the 3D position
- z is the translational axis
- θ is the rotational angle around the vortex
- $\lambda_{dB} = h/mv$ is the de Broglie wavelength
- $\lambda_C = h/mc$ is the Compton wavelength
- $\omega = E/\hbar$ is the angular frequency
- A is an amplitude factor.

A distinguishing feature of this wave function is the explicit inclusion of the rotational phase term, $2\pi\theta/\lambda_C$. This term is intended to capture the internal dynamics of the electron, providing a physical basis for properties such as intrinsic spin, which are typically introduced more abstractly in standard quantum mechanics.

7.1. Derivation of Physical Quantities from the Vortex Model

The geometric structure inherent in the vortex model allows for the derivation of several critical physical quantities from classical and relativistic principles such as Lorentz factor, Bohr orbit circumference and fine-structure constant.

7.1.1. Lorentz Factor Derivation

If the internal rotational speed perpendicular to the translation axis is $v_\perp$, and the total speed of the constituent elements of the vortex is c (the speed of light), the translational speed v can be related to $v_\perp$ and c.

The geometric structure of this model allows for the derivation of critical quantities. The rotational speed perpendicular to the translation axis is given by:

$$v_\perp = \sqrt{c^2 - v^2} \tag{7.1.1.1}$$

This leads to a relativistic Lorentz factor:

$$\gamma = \frac{c}{v_\perp} = \frac{c}{\sqrt{c^2 - v^2}} = \frac{1}{\frac{\sqrt{c^2 - v^2}}{c}} = \frac{1}{\sqrt{\frac{c^2 - v^2}{c^2}}} = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{7.1.1.2}$$

This geometric interpretation aligns with special relativity, showing how time dilation and internal structure are interconnected in the vortex framework.

7.1.2. Bohr Orbit Circumference and De Broglie Wavelength

Using vacuum permittivity ε_0 and known constants:

$$v_0 = \frac{e^2}{h\varepsilon_0} \approx 2.1877 \times 10^6 \text{ m/s}$$

$$\lambda = \frac{h}{mv_0} \approx 3.32 \times 10^{-10} \text{ m}.$$

This matches the Bohr orbit circumference, corresponding to the ground state de Broglie wavelength in hydrogen.

For the central electron vortex:

$$r = 3.86 \times 10^{-13}\ \text{m}$$

Circumference:

$$C = 2\pi r \approx 2.43 \times 10^{-12}\ \text{m}$$

This aligns precisely with the Compton wavelength:

$$\lambda_C = h/mc \approx 2.426 \times 10^{-12}\ \text{m}$$

7.1.3. Fine-Structure Constant Relationship

The fine-structure constant α has long been regarded as one of the most mysterious dimensionless constants in physics. In the author's previous work, "*A New Theory on the Origin and Nature of the Fine Structure Constant*" [25], a novel explanation is proposed based on the vortex model. There, α is interpreted not as a fundamental constant arising from quantum electrodynamics, but as a geometric ratio intrinsic to vortex structures: specifically, the ratio between the rotational velocity at the boundary of the vortex and the speed of light at its center. This model reveals that the constancy of α emerges from the conserved circulation of an irrotational vortex in a superfluid vacuum, providing a natural and derivable origin for its numerical value.

Within this framework, the fine-structure constant appears as the ratio of Compton to de Broglie frequencies:

$$\frac{f_c}{f_{dB}} \approx \alpha^{-1} = 137$$

This indicates that one de Broglie orbital cycle encompasses approximately 137 Compton-scale rotations—directly linking the structure of electron motion in the vortex model to the observed value of α, and grounding its constancy in vortex geometry (see **Figure 1**).

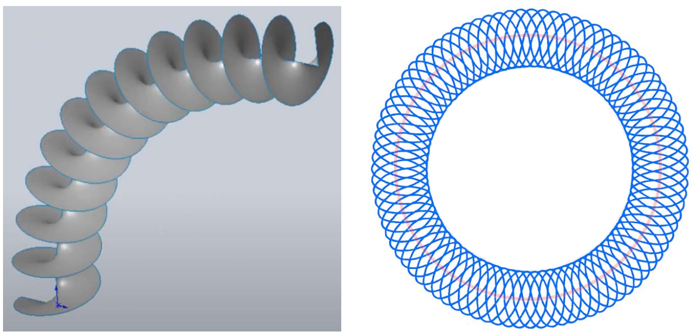

Figure 1. The shape and relationship between de Broglie waves red circle (Bohr orbital) and Compton wavelength blue helix, one circle of de Broglie wave makes 137 Compton waves.

8. The Vortex-Based Schrödinger Equation

Building upon the proposed vortex wave function, this section details the derivation of a new equation of motion, termed the "Vortex-Based Schrödinger Equation". This equation is obtained by applying standard quantum mechanical differential operators to the structured wave function $\psi(z,\theta,t)$ described in Section 5.2.

8.1. Derivation from the Vortex Wave Function

The derivation proceeds by considering the partial derivatives of the vortex wave function with respect to time and the spatial/angular coordinates.

8.1.1. Temporal Derivative

Applying the energy operator, $i\hbar\partial/\partial t$, to the vortex wave function ψ yields:

$$i\hbar\partial\psi/\partial t = i\hbar(-i\omega)\psi = \hbar\omega\psi \tag{8.1.1.1}$$

this directly leads to:

$$i\hbar\frac{\partial\psi}{\partial t} = E\psi \tag{8.1.1.2}$$

the time-dependent Schrödinger equation where E represents the total energy of the system.

8.1.2. Linear Spatial Derivative (along the Z-Axis)

Applying the momentum operator along the z-direction, we analyze the translational component of the phase term in the wavefunction:

$$\psi(r,t) = A\cdot\exp\left[i\left(\frac{2\pi z}{\lambda_{dB}} - \omega t + \frac{2\pi\theta}{\lambda_C}\right)\right] \tag{8.1.2.1}$$

Let the translational phase term be expressed using de Broglie momentum:

$$k_{dB}z = \frac{2\pi z}{\lambda_{dB}} = \frac{p_z z}{\hbar} \tag{8.1.2.2}$$

Applying the operator $-i\hbar\frac{\partial}{\partial z}$:

$$-i\hbar\frac{\partial\psi}{\partial z} = p_z\psi \tag{8.1.2.3}$$

Squaring the operator for kinetic energy, we obtain:

$$-\frac{\hbar^2}{(2m)\frac{\partial^2\psi}{\partial z^2}} = \frac{p_z^2}{2m}\psi = T_{trans}\psi \tag{8.1.2.4}$$

Thus, the spatial part corresponds to standard kinetic energy in the z-direction.

8.1.3. Angular Derivative (Internal Rotation along θ)

The rotational phase term is given by:

$$k_C\theta = 2\pi\theta/\lambda_C = L_z\theta/\hbar \tag{8.1.3.1}$$

Applying the angular momentum operator $-i\hbar\partial/\partial\theta$:

$$-i\hbar\partial\psi/\partial\theta = L_{int}\psi \tag{8.1.3.2}$$

where $L_{int} = mc\lambda_C = \hbar$.

The second derivative corresponds to the rotational kinetic energy operator:

$$-\hbar^2/(2I)\partial^2\psi/\partial\theta^2 = \left(L_{int}^2/2I\right)\psi = T_{rot}\psi \tag{8.1.3.3}$$

where $I = mr^2$ is the moment of inertia with $r = \lambda_C$.

9. Final Vortex Equation of Motion

Combining both translational and rotational components, we arrive at the complete vortex-based evolution equation:

$$i\hbar\frac{\partial\psi}{\partial t} = \frac{\hbar^2\partial^2\psi}{2m\partial z^2} - \frac{\hbar^2\partial^2\psi}{2I\partial\theta^2} + V\psi \tag{9.1}$$

where:

- $\psi(z,\theta,t)$ is the vortex wave function defined in cylindrical coordinates,
- m is the electron mass
- $I = mr^2$ is the moment of inertia of the vortex
- V is a potential term representing external or self-consistent fields.

This vortex-form Schrödinger-like equation captures both translational and intrinsic rotational (spin) degrees of freedom of the electron in a superfluid vacuum.

Thus, this vortex-based wave equation provides a physically grounded alternative to the traditional Schrödinger framework and opens a path toward a real, deterministic quantum mechanics rooted in vacuum vortex dynamics.

The vortex model offers a causal, structured, and fully deterministic framework for the electron. It naturally reproduces key quantum mechanical results—spin $\frac{\hbar}{2}$, de Broglie and Compton wavelengths, Bohr orbit—and aligns with relativity and fluid dynamics.

This unified geometric interpretation lays the foundation for a reformulation of quantum theory, grounded not in statistical axioms but in physical vortex dynamics of the vacuum.

10. Toward a Unified Quantum Theory

This formalism provides a deterministic and causal interpretation of quantum behavior. Unlike the statistical nature of the Copenhagen interpretation, this vortex model derives quantum properties from real fluid dynamics. Key outcomes include:

- Accurate reproduction of de Broglie and Compton wavelengths.
- Natural emergence of spin ($\hbar$) and orbital angular momentum.
- Prediction of electron mass, energy, and fine-structure constant relationships.

By replacing Schrödinger's abstract wavefunction with a geometrically grounded vortex, the model aligns quantum mechanics with classical field theory and opens a path toward unification with general relativity through vacuum vorticity.

11. Validation of the Vortex Model against Quantum Results

In this section, we compare the fundamental quantities derived from the classical vortex model to their quantum counterparts, showing that the two approaches yield equivalent values despite their differing interpretations.

The classical model treats the electron as a self-sustaining superfluid vortex with internal circular motion and external translation, leading to a three-dimensional helical path in space. This structure accounts for the wave-like behavior of the electron as a natural consequence of its geometry and dynamics, rather than invoking abstract probability waves.

Table 2 summarizes the direct comparison between key physical quantities as predicted by standard quantum mechanics and as derived from the classical vortex model of the electron. Despite the differing conceptual frameworks, the two approaches yield numerically equivalent results, validating the vortex model as a physically consistent alternative to probabilistic interpretations.

Table 2. The direct comparison.

Quantity	Quantum Mechanics	Vortex Model
de Broglie Wavelength	$\lambda = h/mv$	$\lambda = h/mv_0$
Compton Wavelength	$\lambda_C = h/mc$	$\lambda_C = 2\pi r$
Momentum	$p = mv$	$p = mv_0$
Spin	$S = \hbar/2$	$L_z = \hbar$
Wave Function	ψ probabilistic	ψ helical
Lorentz Factor	Postulated	$\gamma = c/v_\perp$

12. Comparison of Schrödinger and Vortex Models for Electron Phase

To illustrate the conceptual and mathematical distinctions between the standard quantum mechanical approach and the vortex-based model, we compare the electron phase predictions from both frameworks under identical physical conditions.

Physical Setup

- Electron mass: $m = 9.11 \times 10^{-31}$ kg
- Electron speed: $v = 2 \times 10^{6}$ m/s
- Observation point: $z = 1$ nm $= 1 \times 10^{-9}$ m
- Time: $t = 1 \times 10^{-15}$ s

1) Schrödinger Equation Phase Calculation

Standard wave function:

$$\psi(z,t) = A \cdot \exp\left[i(kz - \omega t)\right]$$

- $p = mv = 1.822 \times 10^{-24}$ kg·m/s
- $k = p/\hbar \approx 1.727 \times 10^{10}$ m^{-1}
- $E = p^2/2m \approx 1.82 \times 10^{-18}$ J
- $\omega = E/\hbar \approx 1.725 \times 10^{16}$ rad/s
- Phase at given point: $kz - \omega t \approx 0.02$ rad

2) Vortex Wave Function Phase Calculation

Vortex model wave function:

$$\psi(r,\theta,t) = A \cdot \exp\left[i\left(\frac{2\pi z}{\lambda_{dB}} - \omega t + \frac{2\pi\theta}{\lambda_C}\right)\right] \tag{12.1}$$

- $\lambda_{dB} = h/mv \approx 3.64 \times 10^{-10}$ m
- $\lambda_C = h/mc \approx 2.43 \times 10^{-12}$ m
- $\theta = \pi$ rad (half rotation)
- $\omega \approx 1.725 \times 10^{16}$ rad/s
- Phase $\approx 0.02 + 8.1 \times 10^{12}$ rad

Summary Comparison

Feature	Schrödinger Model	Vortex Model
Structure	Plane wave	Helical wave with internal rotation
Phase expression	$kz - \omega t$	$2\pi z/\lambda_{dB} - \omega t + 2\pi\theta/\lambda_C$
Phase at $z = 1$ nm, $t = 1$ fs	≈ 0.02 rad	$\approx 0.02 + 8.1 \times 10^{12}$ rad
Interpretation	Probabilistic amplitude	Real helical motion
Internal dynamics	Not specified	Includes spin, rotation

This comparison highlights that while the Schrödinger model captures the external evolution of phase as a function of position and time, the vortex model provides a deeper internal structure by explicitly encoding the rotational dynamics of the electron. The additional angular phase component offers a concrete physical basis for intrinsic spin and angular momentum, aligning with a deterministic and geometrically coherent interpretation of quantum behavior.

When comparing the Schrödinger and vortex-based wave functions, it may appear that they yield different phase results. However, this difference is not a contradiction—it reflects the added physical insight provided by the vortex model.

The Schrödinger wave function is:

$$\psi(z,t) = A \cdot \exp\left[i(kz - \omega t)\right] \tag{12.2}$$

This describes only the translational motion of a free particle.

The vortex wave function is:

$$\psi(r,\theta,t) = A \cdot \exp\left[i\left(\frac{2\pi z}{\lambda_{dB}} - \omega t + \frac{2\pi\theta}{\lambda_C}\right)\right]$$

This includes:

- Translational phase (equivalent to Schrödinger): $2\pi z/\lambda_{dB} - \omega t$
- Rotational phase: $2\pi\theta/\lambda_C$, capturing internal spin-like structure

The rotational term corresponds to angular motion around the vortex core at the Compton scale—absent in the Schrödinger framework.

When $\theta = 0$, the vortex model reduces exactly to the Schrödinger wave function, demonstrating consistency. When $\theta \neq 0$, the vortex model generalizes the wave function to include intrinsic geometry and internal dynamics.

This extended phase is not a flaw—it is a feature that allows the vortex model to recover all quantum predictions while offering a more physically intuitive, structured, and deterministic account of electron behavior.

13. Explaining Interference without Probability

The double-slit experiment is often viewed as evidence of quantum indeterminism—suggesting that electrons interfere with themselves probabilistically. The vortex model, however, offers a deterministic alternative: the electron is a rotating, helical structure combining translational motion (de Broglie wavelength) with internal rotation (Compton wavelength).

As the vortex passes through a slit, the slit geometry alters its internal phase in a predictable way, causing deflections that depend on the vortex's initial angular orientation. Over many events, these deterministic paths form a stable interference pattern, with bright and dark fringes emerging from coherent alignment or misalignment of vortex phases—without invoking wavefunction collapse or self-interference.

To compare this with the standard formalism, recall that the classical quantum model predicts fringe locations using the de Broglie wavelength. For a single slit, dark fringes occur when:

$$a \cdot \sin(\theta) = n \cdot \lambda$$

where a is the slit width, θ is the diffraction angle, and $n \in \mathbb{Z} \setminus \{0\}$. For a double slit, the fringe spacing Δy on a screen a distance L away is given by:

$$\Delta y = \frac{\lambda \cdot L}{d}$$

with d being the slit separation.

In the vortex model, these patterns are still observed, but now explained through the deterministic mechanics of the vortex wavefunction:

$$\psi(r,t) = A \cdot \cos\left(\frac{2\pi z}{\lambda_{dB}} - \omega t + \frac{2\pi\theta}{\lambda_C}\right) \tag{13.1}$$

This formulation includes the same translational structure from the de Broglie wavelength, but adds a rotational phase governed by the Compton scale. The slit acts as a rotational filter, modulating the vortex alignment and generating predictable deflections.

This perspective not only preserves the empirical success of quantum mechanics but restores a continuous, intelligible account of motion. It shows that interference patterns are not inherently probabilistic but can emerge from structured, deterministic behavior when internal dynamics are fully taken into account.

14. The Role of the Observer in the Vortex Interpretation

In contrast to standard quantum theory, the vortex model does not require a wavefunction collapse or the observer to instantiate physical outcomes. The electron's trajectory is governed by deterministic internal and external dynamics. Observation does not alter its nature—it simply detects the structured interaction between the vortex and the measurement apparatus.

The so-called "probabilistic behavior" of quantum systems is thus reinterpreted as the macroscopic averaging of many deterministic vortex trajectories with varying initial phases. Interference patterns emerge not from a particle interfering with itself, but from coherent vortex dynamics shaped by experimental boundaries.

Measurement, in this model, is not a mysterious intervention, but a phase-sensitive interaction that reveals pre-existing structures.

This shift demystifies quantum mechanics by placing the observer back into a classical role: not a creator of outcomes, but a resonator with the underlying geometry of the vacuum.

15. Deriving the Born Rule from Deterministic Vortex Dynamics

One of the most foundational principles of quantum mechanics is the Born rule, which states that the probability density of detecting a particle at a given position and time is given by the squared modulus of its wave function:

$$P(r,t) = |\psi(r,t)|^2 \tag{15.1}$$

In standard quantum theory, this rule is introduced as an axiom. In contrast, the vortex-based model offers a physical explanation: quantum probabilities may emerge naturally from deterministic internal dynamics and ensemble behavior of the vortex structure representing the electron.

15.1. Statistical Emergence from Vortex Phase Ensembles

Consider an ensemble of electrons, each described by a helical vortex wave function of the form:

$$\psi_j(r,\theta,t) = A \cdot \exp\left[i\left(kz - \omega t + \varphi_j\right)\right] \tag{15.1.1}$$

where φ_j is the internal rotational phase associated with the vortex structure of the j-th particle. The total observed amplitude is the coherent sum of individual vortex contributions:

$$\Psi_{total}(r,t) = \sum\nolimits_{j=1}^{N}(r,t) = A \cdot \sum\nolimits_{j} \exp\left[i\left(kz - \omega t + \varphi_j\right)\right]. \tag{15.1.2}$$

The observed intensity, interpreted as probability density, is:

$$P(r,t) = |\Psi_{total}(r,t)|^2 = \left|\sum\nolimits_{j=1}^{N} e^{i\varphi_j}\right|^2. \tag{15.1.3}$$

If the internal phases φ_j are uniformly distributed (*i.e.*, incoherent), the interference terms average out, and the result simplifies to:

$$P(r,t) \propto N \cdot |\psi(r,t)|^2 \tag{15.1.4}$$

This shows that even though each particle follows a deterministic vortex trajectory, the probabilistic distribution observed across an ensemble can emerge from randomization of initial internal phases.

15.2. Time Averaging from Internal Core Oscillations

The vortex core may undergo rapid internal oscillations, similar to the Zitterbewegung effect. These radial oscillations can be modeled as:

$$r(t) = r_0 + \varepsilon \cdot \sin(\Omega t + \theta_0) \tag{15.2.1}$$

where r_0 is the average vortex radius, ε is the oscillation amplitude, Ω is the angular frequency, and θ_0 is the initial phase. Over time, this modulation causes the interaction point between the electron and measurement device to vary.

The long-term average detection probability becomes:

$$P(r) \propto \lim_{T\to\infty} \frac{1}{T} \cdot \int_0^T \left|\psi(r(t))\right|^2 \mathrm{d}t \tag{15.2.2}$$

This result shows that even a single vortex, when sampled over time due to its internal motion, can exhibit a statistical behavior equivalent to the Born rule.

15.3. Ergodic Exploration of Configuration Space

Assume that the vortex core explores a bounded region R in configuration space through its internal dynamics. If this motion is ergodic (*i.e.*, it eventually visits all accessible states), then the fraction of time the vortex spends in a small volume element d V is given by:

$$\frac{\tau(\mathrm{d}V)}{T} \to \int_{\mathrm{d}V} \left|\psi(r,t)\right|^2 \mathrm{d}^3 r \tag{15.3.1}$$

Thus, the probability of detecting the electron in region d V is proportional to the integral of the squared modulus of the wave function over that region—precisely the Born rule.

15.4. Implications and Future Research

These three mechanisms—1) ensemble averaging over internal phases, 2) time-averaging over internal oscillations, and 3) ergodic exploration of space—suggest that the Born rule is not a fundamental randomness, but rather a statistical result of deterministic internal structure.

Future work should focus on:

- Formalizing vortex ensemble dynamics and phase statistics,
- Simulating vortex trajectories with controlled internal parameters,
- Exploring whether deviations from the Born rule can occur under coherent phase conditions.

Ultimately, this perspective aligns with the core philosophy of the vortex model: that quantum behavior arises from deep geometric and fluidic structures in the vacuum, rather than abstract axioms. The Born rule becomes not a mystery, but a mathematically emergent property of vortex-based reality.

16. Why the Vortex Model Satisfies Quantum Requirements

The proposed vortex wave function satisfies key physical criteria expected from any viable quantum theory:

- **Determinism:** The electron follows a defined helical path with no collapse or indeterminism.
- **Realistic Ontology:** The vortex has physical attributes—structure, rotation, and energy flow—making it a real entity, not a probability cloud.
- **Wave-Particle Duality:** The vortex unifies wave and particle aspects through geometry: the internal circular motion defines the Compton wavelength, while translational motion defines the de Broglie wavelength.
- **Quantization:** Energy levels and spin emerge naturally from geometric constraints and rotational symmetry.
- **Relativistic Compatibility:** The model incorporates the Lorentz transformation as a geometric outcome of the velocity decomposition, offering consistency with special relativity.

In this way, the vortex formulation not only aligns with the known predictions of quantum mechanics but grounds them in a coherent and visualizable structure.

17. Resolving Classical Quantum Paradoxes

17.1. Entanglement and the EPR Paradox

Quantum entanglement, famously highlighted by the Einstein-Podolsky-Rosen (EPR) paradox, has posed profound philosophical challenges to deterministic interpretations of quantum mechanics. In standard quantum theory, entanglement describes a condition where the properties of two particles become interlinked, resulting in instantaneous correlations regardless of spatial separation. This phenomenon appears non-local and inherently probabilistic in the conventional interpretation.

In the vortex-based deterministic model presented here, entanglement is reinterpreted as a synchronization of internal vortex phases established during the initial interaction between particles. The internal structure and rotational dynamics of vortex entities can become phase-locked, analogous to classical coupled oscillators. Upon separation, these vortices remain correlated due to the conservation of internal angular momentum and phase coherence. Thus, what quantum mechanics describes as "non-locality" is, within this deterministic vortex framework, a preserved synchronization of phases embedded in the geometry of the vacuum medium.

17.2. Bell's Inequality and Nonlocality

Bell's inequality represents a quantitative test distinguishing classical local realism from quantum mechanics, with experimental evidence favoring quantum predictions and thus suggesting non-local behavior. The vortex framework accommodates Bell-type correlations naturally through the inherent non-local characteristics of vortex fluid dynamics. Specifically, the quantum vacuum is treated as a superfluid medium permitting instantaneous phase adjustments over spatial distances, consistent with vortex hydrodynamics.

In this context, violation of Bell's inequality does not imply faster-than-light signaling or true non-local interactions in the classical sense; instead, it reflects instantaneous coherence adjustments within a single, unified vortex-medium system. Hence, the vortex interpretation resolves Bell's paradox by clarifying non-local correlations as natural outcomes of coherent, structured motion rather than probabilistic quantum leaps or mystical influences.

17.3. Quantum Tunneling

Quantum tunneling, another quintessential quantum paradox, is traditionally explained as a particle probabilistically overcoming a potential barrier through wavefunction penetration. Within the deterministic vortex model, tunneling emerges as a geometrical and hydrodynamical phenomenon. The vortex structure, characterized by internal angular momentum and coherent vacuum flow, interacts with potential barriers through structured resonance conditions. Instead of tunneling probabilistically, the vortex dynamically reconfigures its internal parameters (e.g., radius and angular velocity), enabling passage through or over barriers in a deterministic, coherent fashion.

This interpretation transforms tunneling from a probabilistic anomaly to a predictable resonance phenomenon dependent on internal vortex geometry and vacuum medium interactions.

17.4. Wavefunction Collapse

In standard quantum mechanics, measurement-induced wavefunction collapse poses an interpretational challenge, attributing special status to the observer. The vortex-based model eliminates the necessity for collapse altogether. Measurement outcomes emerge deterministically from interactions between vortices and measurement apparatuses, determined by initial conditions and internal vortex configurations.

Thus, the so-called collapse is merely a selection or resonance with specific vortex phases. Probabilistic outcomes represent averages over many deterministic vortex interactions, effectively demystifying the measurement problem by reestablishing physical continuity and causality.

17.5. Heisenberg's Uncertainty Principle

The uncertainty principle sets fundamental limits on simultaneous precision of complementary variables (position and momentum). Within the deterministic vortex framework, uncertainty reflects practical measurement limitations rather than intrinsic indeterminism. The complex internal dynamics and finite scale of vortex structures inherently restrict simultaneous precision, reflecting classical limitations of measuring extended, rotating bodies rather than fundamental randomness.

In conclusion, classical quantum paradoxes—including entanglement, Bell's inequality, tunneling, wavefunction collapse, and uncertainty—are explicitly and coherently resolved in this deterministic vortex model. Each paradox transforms from a fundamental mystery into a comprehensible, causal, and geometrically grounded feature of vacuum vortex dynamics, fully aligning with empirical quantum outcomes.

18. Discussion

The vortex-based model presented in this work proposes a paradigm shift in our understanding of quantum mechanics, replacing the probabilistic interpretation of the wave function with a deterministic and physically structured view grounded in hydrodynamic principles. By modeling the electron as a self-sustaining vortex in a compressible, superfluid-like vacuum, the model derives key quantum phenomena—including wave-particle duality, interference, spin, and quantization—not from axioms, but from first principles of motion, geometry, and vacuum elasticity.

Unlike the Copenhagen interpretation, where the wave function is a mathematical abstraction encoding probability amplitudes, the vortex model restores physical realism by identifying the wave function with a real helical motion through space and time. Internal rotation gives rise to the Compton wavelength and spin, while external translation produces the de Broglie wavelength. This dual motion results in a helical trajectory that captures the full quantum behavior of the particle within a deterministic framework.

One of the key achievements of this model is its ability to reconstruct the structure of the Schrödinger equation from a physical foundation. The proposed vortex-based wave function includes both translational and rotational phase components, and leads to a generalized evolution equation that accounts for intrinsic spin and internal dynamics—features absent in the original Schrödinger formulation. This equation aligns with hydrodynamic analogs and integrates smoothly with relativistic corrections, offering a natural bridge to quantum field theory.

The resolution of classical quantum paradoxes further illustrates the robustness of the vortex framework. Entanglement and nonlocal correlations, often interpreted as fundamental non-classical mysteries, are here seen as the outcome of phase-locked vortex dynamics embedded in a coherent vacuum medium. Quantum tunneling, uncertainty, and wavefunction collapse are also reinterpreted as manifestations of deterministic vortex geometry and internal phase resonance, rather than inherently probabilistic events.

Importantly, this model addresses the Born rule—a central axiom of quantum mechanics—from a new perspective. By analyzing ensembles of vortex systems, as well as ergodic and chaotic internal motions, it is shown that the statistical distribution described by $|\psi|^2$ can emerge from time-averaged or phase-averaged deterministic behavior. This reframing turns probability from a fundamental mystery into an emergent property, aligning with the broader vision of a causal and structured quantum theory.

Despite its explanatory power, the vortex model opens new questions. The derivation of the Born rule remains semi-formal and requires further mathematical rigor. Likewise, the extension of the model to multi-particle entanglement, relativistic quantum field interactions, and bosonic systems has not yet been fully developed. Furthermore, while the model matches existing quantum predictions, identifying experimental scenarios that could falsify or uniquely verify its principles is an essential next step.

Future research should focus on:

- Simulating vortex ensembles to model complex quantum systems,
- Formalizing the statistical dynamics of phase distributions and vortex-core oscillations,
- Testing for experimental deviations from standard quantum predictions under coherent vortex conditions,
- Generalizing the model to other particles and fields.

In summary, the vortex model offers a unified, deterministic, and geometrically grounded foundation for quantum mechanics. It recovers all essential features of quantum theory while restoring causality, physical structure, and interpretational clarity. Whether this model becomes the new standard or serves as a bridge toward future theories, it marks an important step in our journey toward a deeper understanding of the quantum world.

19. Conclusions

This work presents a comprehensive and physically grounded reformulation of quantum mechanics based on the dynamics of irrotational vortex structures in a superfluid vacuum. By modeling the electron as a self-sustaining helical vortex with both internal rotation and external translation, we have derived fundamental quantum properties—such as spin, mass, charge, de Broglie and Compton wavelengths, and interference patterns—not as postulates, but as emergent features of a unified geometric and hydrodynamic framework.

The vortex-based wave function incorporates both translational and rotational phase components, leading to a generalized evolution equation that extends the Schrödinger formalism while retaining compatibility with relativistic and classical limits. Quantum behaviors traditionally interpreted through probability and collapse are here reinterpreted as deterministic outcomes of structured vortex trajectories and internal dynamics. The Born rule, a cornerstone of quantum measurement theory, emerges naturally from statistical averaging over phase distributions, chaotic core oscillations, and ergodic behavior.

In resolving long-standing quantum paradoxes—including entanglement, tunneling, nonlocality, and wavefunction collapse—the model restores physical realism, causality, and continuity to quantum theory. It shows that quantum uncertainty is not a fundamental indeterminism but a reflection of complex internal dynamics governed by vacuum elasticity and vortex geometry.

This framework not only aligns with empirical observations but offers new directions for theoretical and experimental exploration. It opens a promising path toward reconciling quantum mechanics with classical field theory and general relativity, and provides a platform for the unification of the fundamental forces and particles of nature.

Ultimately, this vortex model transforms the abstract language of quantum mechanics into a physically visualizable and conceptually coherent theory—revealing that beneath the apparent randomness of quantum behavior lies a deeper order woven into the fabric of the vacuum itself.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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