A New Realist Formulation of Quantum Theory

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Abstract

This article presents a new way of looking at and understanding quantum physics through the lens of a novel realist framework. It addresses core issues of realism, locality, and measurement. It proposes a general quantum ontology consisting of two field-like entities, called W-state and P-state, that respectively account for the wave- and particle-like aspects of quantum systems. Unlike Bohmian mechanics, however, it does not take the conjunction of wave and particle literally.

W-state is a generalization of the wavefunction, but has ontic stature and is defined on the joint time-frequency domain. It constitutes a non-classical local reality, consisting of superpositions of quantum waves writ small. P-state enforces entanglement obligations and mediates the global coordination within quantum systems required to bring about wavefunction collapse in causal fashion consistent with special relativity.

The framework brings quantum theory much closer to general relativity. The two share common language, concepts, and principles. It offers a sensible alternative to the Copenhagen dispensation, which actively discourages - indeed, oracularly proscribes - inquiry that seeks to explain quantum mechanics more deeply than the fact that the mathematical formalism works.

Contents

1 Introduction **3**
1.1 Quantum Reality: W-state and P-state . . . 3
1.2 Measurement Problem . . . 3
1.3 Ontology and Epistemology . . . 3
1.4 Quantum Story Telling . . . 4
1.4.1 What? . . . 4
1.4.2 Where? When? . . . 4
1.4.3 How? . . . 4
1.4.4 Why? . . . 4

2 Q-1: Quantum Physics between Measurement Events **5**
2.1 Ontology of Simple Quantum Systems . . . 5
2.1.1 Classical and Quantum Conceptions of Local Reality . . . 5
2.1.2 Classical Wave Ontology . . . 5
2.1.3 Quantum Wave Ontology . . . 5
2.1.4 Superpositions of Quantum Waves . . . 6
2.1.5 Time-Frequency Representation of W-state . . . 6
2.1.6 W-state Current Density . . . 6
2.1.7 Rest Manifolds . . . 6
2.2 W-State Dynamics and Causation . . . 7
2.2.1 Thread Dynamics . . . 7
2.2.2 Thread Phase . . . 7
2.2.3 Causal Structure of W-state . . . 8
2.2.4 Free Quanton Dynamics . . . 8
2.2.5 Classical Limit . . . 8
2.3 Wave Mechanics . . . 9
2.3.1 Rigidity of Wave Mechanics . . . 9
2.3.2 Hamiltonian Formulation of the Schrödinger Equation . . . 9
2.3.3 Wavepacket Expansion . . . 9
2.4 Spin . . . 10
2.4.1 Spin Up, Spin Down . . . 10
2.4.2 Superposition of Spin Up and Spin Down . . . 10
2.4.3 Spin Quantum Number . . . 10
2.4.4 Spin Dynamics and Flexure . . . 11
2.5 Systems of Identical Quantons . . . 11
2.5.1 Multi-Quanton W-state . . . 11
2.5.2 Tight Superpositions . . . 11
2.5.3 Spin-Statistics Theorem . . . 11
2.5.4 Fermion Exclusion . . . 12

3 Q-2: Physics of Quantum Measurement **12**
3.1 Measurement Events . . . 12
3.1.1 Conservative and Non-conservative Forces . . . 12
3.1.2 Intractibility of the Measurement Problem . . . 12
3.2 Non-Locality . . . 13
3.2.1 Strong Non-Locality . . . 13
3.2.2 Weak Non-Locality . . . 13
3.2.3 Absolute Randomness . . . 14
3.2.4 Dynamic Implications of Weak Non-Locality . . . 14
3.3 Measurement Event Dynamics . . . 14
3.3.1 Measurement Cross-Section Density . . . 14

3.3.2 Non-Deterministic W-state Evolution . . . 14
3.3.3 Statistical Form of W-state Dynamics . . . 15
3.3.4 Quantum Information . . . 15
3.4 Measurement Outcome Correlations . . . 15
3.4.1 Multiple Measurement Sites . . . 16
3.4.2 Decentralized Innovation and Arbitration . . . 16
3.4.3 Innovation Components . . . 16
3.4.4 Measurement Outcome Computation . . . 17
3.4.5 Natural Computation . . . 17
3.5 Entanglement . . . 17
3.5.1 Entangled Quanton Pairs - Double Measurements . . . 17
3.5.2 Entangled Quanton Pairs - Single Measurements . . . 18
3.5.3 P-state . . . 18
3.5.4 Wavefunction Collapse - Full Detection . . . 18
3.5.5 Wavefunction Collapse - Partial Detection . . . 18
3.5.6 P-state Evolution Between Measurement Events . . . 19
3.6 Measurement Processes . . . 19
3.6.1 Externally Triggered Measurement Events . . . 19
3.6.2 Internally Triggered Measurement Events . . . 20
3.6.3 Wavepacket Expansion or Random Walk? . . . 20
3.6.4 Spontaneous Emission . . . 21
3.6.5 Time-Dependent Perturbation Theory . . . 22

4 Realist Framework vis-à-vis Other Interpretations 22
4.1 Pilot Wave Theory . . . 22
4.1.1 Pilot Wave Theory - Force Law . . . 22
4.1.2 Assessment of Pilot Wave Theory . . . 23
4.2 Many Worlds . . . 23
4.2.1 Primacy of the Wavefunction . . . 23
4.2.2 Denialist Stance on Measurement . . . 23
4.2.3 Many Worlds Complexity . . . 23
4.3 Objective Collapse Theories . . . 24
4.3.1 Coexistence of Rules 1 and 2 . . . 24
4.3.2 Micro-Measurement Model Detail . . . 24
4.4 Copenhagen . . . 24
4.4.1 Schrödinger's Cat . . . 24
4.4.2 HUP and Wavefunction Collapse . . . 24
4.4.3 Dogmatic Anti-Realism . . . 25

1 Introduction

1.1 Quantum Reality: W-state and P-state

The ontology of quantum systems is envisaged as a pair of two field-like entities, called W-state and P-state, that are distributed in the four-dimensional space-time of special relativity. W-state is essentially an ontic conception of the wavefunction and accounts for the wave-like behavior of quantum systems (the simplest types of which are generically called *quantons*). For the most part, W-state evolves deterministically, much like in the Schrödinger and Dirac equations. P-state dynamics, by contrast, are intricately non-local and depend sensitively on the outcomes of measurement events. P-state enforces entanglement obligations and mediates the global coordination within quantons required to bring about wavefunction collapse in causal fashion consistent with special relativity. P-state is necessary to account for the particle-like behavior of quantons, as well as strong measurement outcome correlations that cannot be explained by local hidden variables theories. It is the missing link that gives the completion of quantum state description that W-state alone cannot provide[1].

W-state and P-state jointly constitute the ontology of individual quantum systems. A primary focus of the technical development that follows is the causal dynamic structure of W-state and P-state.

1.2 Measurement Problem

Quantum physics is governed by two altogether different dynamics principles, namely Rule 1[2] (deterministic evolution of the wavefunction) and Rule 2 (wavefunction collapse precipitated by measurement events). The dichotomy implicitly countenances the notion of two qualitatively different forms of interaction between quantons and their surroundings. Rule 1 interactions involve forces of a simple kind (*e.g.*, Coulomb field of a nucleus) that are conservative in nature and mesh smoothly with the W-state dynamics. Rule 2 interactions, by contrast, involve forces of a fitful disruptive character that cause the W-state to change non-deterministically.

In the realist framework, measurement events are perfectly ordinary physical processes and can arise from interactions with surrounding systems of any size - not just large classical instruments. The measurement problem is demystified and solved, once the causal dynamics of W-state and P-state become understood.

1.3 Ontology and Epistemology

From the outset, quantum mechanics has identified, drawn attention to, and stressed fundamental limitations on information that can be extracted from quantum systems through experimental intervention.

In the realist perspective, a quanton is interrogated and manipulated through a sequence of contrived probings, as a result of which the W-state evolves in non-deterministic fashion governed statistically by an ontic counterpart of the Born Rule. That evolution becomes manifest to the quanton's surroundings, which acquire partial information about the post-measurement W-state. From a statistical learning standpoint, the process through which the experimentalist acquires information from the quanton can be modeled mathematically as a Kalman filter, Bayesian learning machine, or similar algorithmic construct. The picture of the quantum state[3] inferred from the process is informationally equivalent to the pre-measurement *epistemic* wavefunction, which is indeed subject to fundamental limitations of complementarity and the Heisenberg uncertainty principle (HUP).

In the realist framework, the conventional epistemic understanding of quantum mechanics, including the Born Rule, follows as a deductive consequence of the deep ontic formulation in terms of W- and P-state. In this respect, the realist framework rejects the historical stance of Bohr and Heisenberg, who maintained that the measurement outcomes themselves represent the deepest level of quantum reality [9].

Observations extracted from experiment correlate strongly with, *but do not literally or completely represent*, post-measurement W-state. As a simple example, consider a position measurement, for which the observable is a single number (nominal position). That correlates with a dramatic narrowing of the spatial extent of the W-state, but the W-state does not collapse literally to a single point of zero spatial extent.

The new framework recognizes two forms of uncertainty. Epistemic uncertainty is what Heisenberg identified and described. Ontic uncertainty pertains to physical limitations on the compressibility of W-state. Generally

[1]The realist framework affirms the incompleteness of the wavefunction that Einstein historically pointed out.

[2]This terminology is borrowed from Smolin [13].

[3]The picture, obtained from an ensemble of identically prepared instances of the experiment, is $|\Psi|^2$.

speaking, the W-state of a quanton cannot be pinched down to less than the Compton wavelength[4]. Ontic uncertainty is not a matter of ignorance but of fuzziness, *i.e.*, objectively real grayness.

1.4 Quantum Story Telling

The realist framework promises to make physics intelligible once again. Quantum mechanics, as it is customarily presented in textbooks, does not meet basic criteria of what it takes to tell a story: a story about how nature *is*. It is unable to answer questions of what, where, when, and how.

1.4.1 What?

After a century, there is no consensus among experts about the reality status or meaning of the underlying subject matter of quantum theory. It is not a settled matter even what an electron is [7]. According to the historically dominant anti-realist Copenhagen dispensation, the term *electron* signifies not an objectively real microscopic entity, but merely a symbol appearing in the expression of a wavefunction, which is itself nothing more than a calculational device to predict statistical outcomes of experiments. As Bohr famously said: "There is no quantum world. There is only an abstract quantum description."

1.4.2 Where? When?

Quantum mechanics is unable to provide a clear detailed picture of how Rule 1 and Rule 2 dynamics jointly play out in space-time in individual systems. It is sketchy because it is not rooted in any conception of local physical reality and laws founded thereupon. It has no well-known governing equation transparently equivalent to Newton's Second Law and thus cannot provide explanation in terms of local causation. It speaks in entirely different language (*i.e.*, abstract Hilbert spaces) from classical physics [8]. The entire problem of quantum gravity has to do with the fact that quantum mechanics and general relativity do not mesh, because the two are such odd-couple opposites of one another [1, 14].

1.4.3 How?

Quantum mechanics cannot explain what measurement events are or delineate them as objectively real physical processes describable in straightforward physics terms. It offers no explanation for how wavefunction collapse is triggered, how it is coordinated globally within quantum systems that are distributed in space-time, or how an actual outcome that conforms statistically to a certain probability distribution is selected. Historically, the mainstream stance, ostensibly rooted in logical positivism, has been to dismiss such questions as meaningless by denying that the wavefunction has any ontic stature.

1.4.4 Why?

It is an outstanding challenge and obligation for the realist framework to explain why quantum mechanics works and has never been falsified by experiment, despite the century-long disarray on the foundational issues.

But does quantum mechanics work? It is not an entirely unclouded matter, for at least two reasons. One is the issue of renormalization. Quantum electrodynamics (QED) is renowned and celebrated for the unsurpassed precision with which its theoretical predictions match experiment, but even that is not unambiguously settled. Historically, researchers have produced a number of different calculational paths, rooted in dissimilar physical and mathematical assumptions[5], that have all led to ostensibly fantastic agreement with experimental results for the Casimir effect [16] and the Lamb shift [3].

It is also fair to ask whether the foundational issues have caught up with quantum mechanics and ultimately prevented fundamental physics from progressing. Quantum mechanics had a remarkably good run in the middle decades of the 20th century, but it now appears to have worked only up to a point. In the last fifty years, it has had little definitive success in advancing fundamental physics beyond the Standard Model.

[4]This is a fuzzy lower bound on the spatial extent over which the local W-state is appreciably non-zero, not a hard inequality.
[5]There is no definitive repository of publicly available source code for the QED calculations of Feynman, Schwinger, or Bethe.

2 Q-1: Quantum Physics between Measurement Events

2.1 Ontology of Simple Quantum Systems

2.1.1 Classical and Quantum Conceptions of Local Reality

In classical physics, local reality can be represented mathematically by tensor fields, *i.e.*, scalars, vectors, or higher-order tensors. In electromagnetic theory, for example, local reality is the combination of an electromagnetic field tensor and a current density 4-vector. In general relativity, it is the combination of space-time curvature and energy-momentum tensors. Tensors are collections of real-valued physical quantities that come with certain transformation methods that account for how different observers would describe the same underlying beable structures.

In the quantum realm, local reality is very different. Its wave-like part (W-state) consists of superpositions of quantum wave elements. To appreciate what this means, it is necessary to illuminate fundamental differences between classical and quantum waves.

2.1.2 Classical Wave Ontology

In a classical wave, a physically real and mathematically real-valued tensor quantity oscillates at each point in space occupied by the wave. At certain times, it can be said objectively that that quantity is at a peak. At other times, it is zero. Physical reality is the set of tensor values at all points that the system occupies.

Classical wave theory builds upon the mathematical foundation of Fourier analysis, which holds that functions defined on the space-time domain can be expressed in equivalent form in the wavenumber-frequency[6] domain, and vice versa. Mathematically, either representation is complete and convertible to the other. Physically, however, waves are emergent phenomena that arise from the collective properties of tensor field values over finite regions of space (spanning at least several wavelengths). For this reason, the time domain is regarded as *ontically primary* in the classical realm, whereas the frequency domain is of secondary stature.

2.1.3 Quantum Wave Ontology

Consider the simplest quantum system, which is a pure quantum wave. Mathematically, it can be represented by a conventional wavefunction, *viz.*,

$$\psi(\underline{x}, t) = e^{i\omega t} \tag{1}$$

The meaning of complex-valued quantities in quantum physics, such as on the right-hand side of Eq. 1, is altogether different from that in classical physics. Complex-valued quantities are commonly used to represent classical waves, but only as a mathematical convenience to simplify algebraic analysis. In classical wave-theoretic application problems, the real part of the complex-valued quantity[7] represents the physical ontology of interest.

In the quantum realm, the real part of the wavefunction has no physical significance. In quantum waves, there is no physically meaningful notion of crests, troughs, or zeros. In fact, the wavefunction expression in Eq. 1 says nothing *about* local physical reality at the point $(\underline{x}, t)$ in isolation[8]. It is meaningful to speak only of the phase difference between wavefunction values at two different points. In this way, the ontology of quantum waves is inherently *relational* in nature.

According to Eq. 1, *phase*, which is a distinctly quantum concept, is constant on manifolds of constant time (t). This property uniquely defines the rest frame of the quantum wave. Phase differences are defined operationally in terms of superposition: If the states represented by the wavefunction at two different points were collocated[9] at a single point, they would interfere constructively (destructively) if they are in phase (out of phase).

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[6]For brevity, these will be referred to henceforth simply as the time and frequency domains.

[7]In the construction of the complex-valued quantity, the imaginary part is derived as the Hilbert transform of the real part.

[8]Other than whether or not it is zero, which is not the case in Eq. 1 at any point.

[9]This is formalized as an *active transformation*.

2.1.4 Superpositions of Quantum Waves

Consider next a Fourier combination of pure quantum waves, *viz.*,

$$\psi(\underset{\rightarrow}{x}) = \int \tilde{\psi}(\underset{\rightarrow}{k}) e^{i(\underset{\rightarrow}{k} \cdot \underset{\rightarrow}{x})} \, d\underset{\rightarrow}{k} \tag{2}$$

which employs 4-vector notation $\underset{\rightarrow}{k} \equiv (\underline{k}, \omega/c)$ and $\underset{\rightarrow}{x} \equiv (\underline{x}, ct)$. Eq. 2 represents a set of wave components that intersect the point $\underset{\rightarrow}{x}$ but have different velocities relative to an observer[10], who describes each component in terms of a wavenumber ($\underline{k}$) and frequency (ω).

The summation in Eq. 2 signifies *superposition.* The wave components have definite amplitude ratios and phase shifts relative to one another at $\underset{\rightarrow}{x}$, by virtue of their coexisting at that point.

2.1.5 Time-Frequency Representation of W-state

W-state consists of superpositions of quantum waves, *writ small.* This requires a slight modification of Eq. 2, *viz.*,

$$\psi(\underset{\rightarrow}{x}) = \int \tilde{\psi}(\underset{\rightarrow}{k}, \underset{\rightarrow}{x}) e^{i(\underset{\rightarrow}{k} \cdot \underset{\rightarrow}{x})} \, d\underset{\rightarrow}{k} \tag{3}$$

Eq. 3 is a generalization of Eq. 2, but with the important difference that $\tilde{\psi}$ depends on $\underset{\rightarrow}{x}$ as well as $\underset{\rightarrow}{k}$. It denotes a *local Fourier transform.*

Mathematically, W-state is represented definitively and completely[11] by $\tilde{\psi}(\underset{\rightarrow}{k}, \underset{\rightarrow}{x})$, which is a function defined on the time and frequency domains *jointly.* In the quantum realm, the joint time-frequency domain is ontically primary. Quantum waves, unlike their classical counterparts, have ontic stature. Phase relationships between points are physically real in their own right and exist locally (and therefore well below wavelength scale).

The $\underset{\rightarrow}{x}$-dependence in $\tilde{\psi}(\underset{\rightarrow}{k}, \underset{\rightarrow}{x})$ allows the Fourier combinations of waves to vary freely throughout the regions of space-time occupied by a quanton. The $\underset{\rightarrow}{x}$-dependence, however, precludes the inverse Fourier transform. It follows that the wavefunction, $\psi(\underset{\rightarrow}{x})$, is remiss in that it contains less information than $\tilde{\psi}(\underset{\rightarrow}{k}, \underset{\rightarrow}{x})$. Because the W-state itself is incomplete, the wavefunction can be said to be a doubly incomplete description of deep quantum reality.

2.1.6 W-state Current Density

From a practical perspective, the W-state, like the wavefunction, is consequential only insofar as it has bearing on or provides insight into outcomes of measurement events. In the realist framework, at least two emergent aspects of W-state are important in this respect.

From the W-state, a current density 4-vector, $\underset{\rightarrow}{J} \equiv (\underline{J}, c\rho)$, can be derived, wherein the density, ρ, equates to the squared wavefunction amplitude, $|\psi|^2$, in the Born Rule, which yields the probability distribution of outcomes of a specified type of measurement process. The current density depends sensitively on interference effects and is the conduit through which W-state - indeed, all evidence of the wave-like aspect of the quantum realm - becomes manifest to the quanton's surroundings.

2.1.7 Rest Manifolds

The second emergent aspect of W-state is the concept of *rest manifolds.* These are stacks of Cauchy manifolds[12] that are tangent to constant-time manifolds in the local rest frame, wherein the net momentum is zero, *viz.*,

$$\int \left| \tilde{\psi}(\underset{\rightarrow}{k}, \underset{\rightarrow}{x}) \right| \underline{k} \, d\underset{\rightarrow}{k} = \underline{0} \tag{4}$$

in which $\underline{k}$ is the wavenumber 3-vector obtained from the 4-vector $\underset{\rightarrow}{k}$ in the local rest frame.

Rest manifolds provide a generalized definition of rest frame for quantons. In the context of measurement events that are distributed in space-time, rest manifolds provide a natural synchronization mechanism. As such, they are key to solution of the general problem of quantum measurement.

[10] Meaning a passive observer, in the sense of special relativity.

[11] $\tilde{\psi}(\underset{\rightarrow}{k}, \underset{\rightarrow}{x})$ represents only translational W-state, which is a complete description only for spinless quantons devoid of substructure.

[12] A *Cauchy manifold* is a 3D manifold in space-time, any two points on which are space-like separated.

2.2 W-State Dynamics and Causation

The formulation of W-state in the time-frequency domain enables the impartation to quantum theory of what was lost in the historic gestation of quantum mechanics: not only a clear conception of local physical reality, but also dynamics laws driven by local causation.

2.2.1 Thread Dynamics

In classical systems driven by conservative forces, trajectories describing actual evolution of the state can be interpreted as least-action paths. The same is true in the quantum realm, wherein least-action paths are called *threads.*

Thread trajectories are governed by dynamics that are similar to those of classical point particles. The dynamics are governed by a Lagrangian function, *viz.*,

$$L(\underline{x}, \dot{\underline{x}}) \tag{5}$$

in which $\underline{x}$ and $\dot{\underline{x}}$ respectively denote the position and velocity at a point on the thread trajectory. In general, the functional form of the Lagrangian depends on intrinsic attributes of the quanton (*e.g.*, mass, electric charge) and the force fields (*e.g.*, Coulomb attraction between electron and nucleus) driving the dynamics between measurement events.

The Lagrangian yields a dynamics equation in the form of Newton's Second Law, *viz.*,

$$\dot{\underline{p}} = \underline{F} \tag{6}$$

in which $\underline{p}$ is the momentum, *viz.*,

$$\underline{p} \equiv \frac{\partial L}{\partial \dot{\underline{x}}} \tag{7}$$

and F is the force acting on the thread, *viz.*,

$$\underline{F} \equiv \frac{\partial L}{\partial \underline{x}} \tag{8}$$

The Hamiltonian, *viz.*,

$$H \equiv \underline{p} \cdot \dot{\underline{x}} - L \tag{9}$$

yields the joint evolution of thread position and momentum, *viz.*,

$$\dot{\underline{x}} = \frac{\partial H}{\partial \underline{p}} \tag{10a}$$

$$\dot{\underline{p}} = -\frac{\partial H}{\partial \underline{x}} \tag{10b}$$

Threads have well-defined position ($\underline{x}$) and momentum ($\underline{p}$), which jointly constitute thread kinematic state.

2.2.2 Thread Phase

Tangent to any point, $\underset{\rightarrow}{x}$, on a thread is the quantum wave component corresponding to $\tilde{\psi}(\underset{\rightarrow}{k}, \underset{\rightarrow}{x})$, in which $\underset{\rightarrow}{k}$ is directly proportional to the energy-momentum, $\underset{\rightarrow}{p} \equiv (\underline{p}, E/c)$, through Planck's constant, *viz.*,

$$E = \hbar\omega \tag{11a}$$

$$\underline{p} = \hbar\underline{k} \tag{11b}$$

At each point on the thread, the momentum, $\underline{p}$, is obtained from the solution of Eq. 10b, and the energy, E, is equal to the Lagrangian function evaluated at the current position and velocity. The phase difference between the wave components tangent to the thread at points $\underline{x}_A$ and $\underline{x}_B$ is $\vartheta = S/\hbar$, in which S is the action integral, *viz.*,

$$S \equiv \int_{\underline{x}_A}^{\underline{x}_B} L(\underline{x}, \dot{\underline{x}})\, dt \tag{12}$$

Eq. 12 is centrally important to the conception of quantum ontology, which must be described in relational terms. Whereas superposition, as in Eq. 3, enables us to speak of amplitude and phase relationships between two threads by virtue of their intersecting at a point, Eq. 12 provides the only means of speaking of phase relationships at two different points in space-time. For this reason, thread dynamics and trajectories are integrally part and parcel of the beable structure of quantons.

2.2.3 Causal Structure of W-state

The W-state at the upper limit of integration in Eq. 12 is causally determinate from that at the lower limit by virtue of their being interrelated through the common thread dynamics, *viz.*,

$$\tilde{\psi}((\underset{\rightarrow}{k})_B, (\underset{\rightarrow}{x})_B) = \tilde{\psi}((\underset{\rightarrow}{k})_A, (\underset{\rightarrow}{x})_A) \cdot e^{iS/\hbar} \tag{13}$$

In any quanton, infinitely many threads notionally fill the entire region of space-time that its W-state occupies between measurement events. Each point in the region is intersected by multiple threads with different velocities; the wave components tangent to the threads at the point interpenetrate and superpose with one another. The total set of threads constituting the quanton[13] establishes the causal structure of the W-state.

To simulate the dynamic evolution of W-state, $\tilde{\psi}(\underset{\rightarrow}{k}, \underset{\rightarrow}{x})$ must be initialized for all $\underset{\rightarrow}{x}$ on a Cauchy manifold. Once the W-state has been initialized[14], the Hamilton equations, along with integration of phase rate (ω) on the threads, deterministically yields the W-state at all points causally downstream of the manifold. The deterministic evolution of W-state can be regarded as an ontic generalization of the Schrödinger and Dirac equations.

2.2.4 Free Quanton Dynamics

In the simple dynamic scenario of a free quanton, the Lagrangian function is translationally invariant and equal to the total energy, *viz.*,

$$E = (m^2c^2 + p^2)^{1/2}c \tag{14}$$

expressed as a function of the velocity. In Eq. 14, m denotes the quanton rest mass. The solutions of the Hamilton equations are straight-line trajectories with constant velocity, and the rest manifolds are stacks of flat 3D Cauchy manifolds. In the general case, by contrast, the thread trajectories are curvilinear, and the rest manifolds are warped.

With a translationally invariant Lagrangian, the W-state components are independent of $\underset{\rightarrow}{x}$, and Eq. 2 holds. In this scenario, the wavefunction, ψ, *is* complete and can be regarded as having ontic stature in that the W-state, $\tilde{\psi}$, can be obtained from the inverse Fourier transform from the time to the frequency domain.

2.2.5 Classical Limit

In the limit of $\hbar \to 0$, the realist theory of W-state ontology and dynamics reduces seamlessly to classical physics. The thread kinematics coincide with the particle trajectories in a classical ensemble, and single-particle trajectories follow from highly localized W-state initializations. The quantum and classical realms are united under a single formalism and theoretical roof.

At least two effects that are important in the quantum realm disappear in the limit of $\hbar \to 0$. Because the phase rate, ω, is physically consequential in the superposition patterns it produces, the energy level expressed by the Lagrangian, as employed in Eq. 12, is absolute. In the classical limit, phase rate becomes infinite, and Eq. 12 no longer applies. The Lagrangian remains relevant only in the expression of Newton's Second Law, wherein it is indeterminate to within an additive constant.

In the Aharonov-Bohm (AB) effect, interference effects depend directly on the electromagnetic potential field $(\boldsymbol{A}, \phi/c)$. The effects are gauge-invariant, but cannot be derived from the electromagnetic fields ($\boldsymbol{E}$ and $\boldsymbol{B}$) alone. Alternatively interpreted, the AB effect cannot be explained without explicit incorporation of the potential field into the Lagrangian [15]. In the quantum realm, $(\boldsymbol{A}, \phi/c)$ has ontic stature in its own right, but that ceases to be apparent in the limit of $\hbar \to 0$. The electromagnetic dependence in the Lagrangian seamlessly reduces to local

[13] Threads constitute the causal structure of the quanton W-state, but they are not material elements that sum to a whole.

[14] For each $\underset{\rightarrow}{x}$ on the Cauchy manifold, $\tilde{\psi}(\underset{\rightarrow}{k}, \underset{\rightarrow}{x})$ must be specified for all values of $\underset{\rightarrow}{k}$.

interaction with the electromagnetic field tensor and can be expressed entirely in terms of $\boldsymbol{E}$ and $\boldsymbol{B}$, consistent with classical electromagnetic theory.

In the limit of $\hbar \to 0$, rest manifolds are still mathematically well-defined and remain important in the context of non-locality and the measurement problem.

2.3 Wave Mechanics

Wave mechanics, in the historical context, signifies the incorporation of classical wave-theoretic principles into quantum mechanics. It has relied on the assumption of completeness of the wavefunction, $\psi(\underset{\rightarrow}{x})$. It primarily encompasses: (*i*) formulation of Rule 1 dynamics entirely in terms of the wavefunction, such as in the Schrödinger equation, and (*ii*) HUP, which is a mathematical deduction that rests on assumption of wavefunction completeness.

2.3.1 Rigidity of Wave Mechanics

In realist terms, the wavefunction is complete only if it is informationally sufficient to reveal the full W-state. This holds if and only if the Lagrangian is translationally invariant. The solution of the Hamilton equations furnishes a complete picture of a global quantum reality, consisting of threads moving forever in straight lines (or, equivalently, pure quantum waves, such as in Eq. 1, of infinite extent). It is an extremely artificial picture, but it nevertheless represents the actual application of wave mechanics in the quantum realm.

In practice, wave mechanics is used to craft static combinations of pure waves that satisfy boundary conditions in the time domain. It relies fundamentally on phase cancellations[15] to achieve spatial boundedness. From the mathematical perspective, that is useful fiction that serves the purpose of solving many a boundary condition problem in applied physics. From the physical perspective, however, it is remiss. Wave mechanics is not, in its own right, a physical theory capable of accounting for how waves are created, destroyed, or dynamically modified[16]. Quantum mechanics, in its conventional formulation, has no natural way of doing that, since pure waves are as non-local as can be. It follows that quantum mechanics is not a truly dynamic theory on a par with classical physics.

The limitations of wave mechanics in application to the quantum realm are not merely philosophical curios; they have profound implications for the health of quantum theory *per se*. They make quantum mechanics awkward, inflexible, and unamenable to reformulation or alternative forms of expression.

2.3.2 Hamiltonian Formulation of the Schrödinger Equation

One example of the awkwardness is the Schrödinger equation itself, which was historically discovered through heuristic analogy to the Hamiltonian formulation of classical mechanics. The analogy proved successful and became part of the received wisdom and practical working knowledge of 20th-century physics, which moved on to less philosophical priorities.

In classical mechanics, the Hamiltonian formulation is derived from Newton's Laws, with the Lagrangian formulation as an intermediate step. In the quantum realm, however, the Schrödinger equation defies easy reverse engineering and reformulation backwards to more basic form akin to Newton's Second Law. This severely limits the expressiveness of quantum mechanics, which cannot account for local causation. It impedes the leap from conservative to non-conservative forces (analogous to friction in classical mechanics) that must be made to understand measurement processes and how they cause non-deterministic evolution of the W-state.

2.3.3 Wavepacket Expansion

A second example is wavepacket expansion. According to conventional quantum theory, a free quanton whose wavefunction is initially concentrated spreads out with the passage of time. For a Gaussian wave packet of width Δ_0 at initial time $t = 0$, the width at future time $t > 0$ is [12]:

$$\Delta(t) = \Delta_0 \left[1 + \left(\frac{\hbar t}{m \Delta_0^2} \right)^2 \right]^{1/2} \tag{15}$$

[15] $\psi(\underline{x}, t)$ is spatially bounded (*i.e.*, square-integrable) only because of phase cancellation (*i.e.*, destructive interference) amongst the wave components at points far removed from the wavefunction center.

[16] This makes it extremely difficult to square wave mechanics with wavefunction collapse.

The standard solution technique takes the Fourier transform of the initial packet to go from $\psi(\underline{x}, 0)$ to $\tilde{\psi}(\underline{k}, \omega)$. The wavefunction is then propagated forward in the frequency domain to time t and transformed back to the time domain to obtain $\psi(\underline{x}, t)$.

The result in Eq. 15 is peculiar in two respects. First, it is an epistemic result that hinges on the initial conditions at $t = 0$, but it does not smell right as an ontic description of W-state diffusion for a free quanton. According to Eq. 15, the variance is nearly constant for small t but then eventually grows quadratically for large t. A linear variance growth rate of $\hbar/m$ at all times seems at least as plausible an ontic model. Second, $\Delta(t)$ is a symmetric function of time, implying that the state at $t = 0$ is special and qualitatively different from states at all other times.

2.4 Spin

In the realist framework, spin is regarded as anisotropic local W-state.

2.4.1 Spin Up, Spin Down

Consider the simple case of W-state, for a pure wave in its rest frame, described as "spin up" with respect to the $+\hat{z}$-axis. The application of the rotation operator, $\boldsymbol{R}(\hat{z}, \vartheta)$, to the W-state signifies an active transformation, which yields a physical rotation of the original W-state (operand) about the $+\hat{z}$-axis through angle ϑ. The rotated spin up state is related to the unrotated through a positive phase shift, *viz.*,

$$\boldsymbol{R}(\hat{z}, \vartheta) \cdot \uparrow_{\hat{z}} = e^{is\vartheta} \cdot \uparrow_{\hat{z}} \tag{16}$$

in which s is a spin quantum number. The rotated spin down state is related to the unrotated through a negative phase shift, *viz.*,

$$\boldsymbol{R}(\hat{z}, \vartheta) \cdot \downarrow_{\hat{z}} = e^{-is\vartheta} \cdot \downarrow_{\hat{z}} \tag{17}$$

Any two W-states satisfying the aforementioned description of "spin up" are the same modulo a multiplicative scalar, and similarly for spin down.

2.4.2 Superposition of Spin Up and Spin Down

Consider a reference spin up state, $\uparrow_{\hat{z}}$, and a reference spin down state, $\downarrow_{\hat{z}}$, both of unit amplitude. The superposition of the two is aligned along a geometric axis (which may be labeled $+\hat{x}$) perpendicular to $\hat{z}$, *viz.*,

$$\uparrow_{\hat{z}} + \downarrow_{\hat{z}} = \uparrow_{\hat{x}} \tag{18}$$

There is no absolute number that can be ascribed to the phase difference between the up and down reference states (let alone their individual phases), but the phase difference finds physical expression in the particular geometric axis on which the superposition is aligned.

2.4.3 Spin Quantum Number

Consider rotation of the superposition about about the $+\hat{z}$-axis through angle ϑ. The rotation operator is distributive, from which one obtains:

$$e^{is\vartheta} \cdot \uparrow_{\hat{z}} + e^{-is\vartheta} \cdot \downarrow_{\hat{z}} = \boldsymbol{R}(\hat{z}, \vartheta) \cdot \uparrow_{\hat{x}} \tag{19}$$

In the case of $\vartheta = 2\pi$, $\uparrow_{\hat{x}}$ undergoes rotation through a full geometric revolution, which returns to a state of spin aligned along the $+\hat{x}$-axis. It follows that $\boldsymbol{R}(\hat{z}, 2\pi)$ must be a scalar, and in conjunction with Eq. 18 that the phase factors on the left-hand side of Eq. 19 must be equal. The spin quantum number, s, must therefore be either integer or half-integer. This corroborates empirical fact that nature hosts two types of quantons: (i) fermions, for which s is half-integer, and (ii) bosons, for which s is whole integer.

For bosons, rotation through $\vartheta = 2\pi$ restores the original state. For fermions, rotation through $\vartheta = 2\pi$ yields the negative of the original state; rotation through $\vartheta = 4\pi$ restores the original state.

2.4.4 Spin Dynamics and Flexure

For spinless quantons ($s = 0$), the W-state is isotropic, and its dynamics depend only on translational state. Quantons with spin additionally have rotational state, which consists of position (spin axis alignment) and velocity. Spin axis alignment can be visualized as a vector arrow strapped onto each thread. The translational and rotational components of thread state jointly evolve under a single Hamiltonian.

In the realist framework, spin is local, and spin fields can exhibit *flexure*, *i.e.*, spin alignment variation within quantons. This allows for spin-orbit coupling to play out locally through the dynamics laws. In conventional quantum theory, by contrast, quanton spin is monolithic and described entirely by two numbers: spin magnitude (s) and projection (s_z) onto any one geometric axis.

2.5 Systems of Identical Quantons

The theoretical development up to this point has encompassed only single quantons. Its extension to systems of multiple quantons is now addressed.

2.5.1 Multi-Quanton W-state

The multi-quanton W-state at a given point consists of a list of single-quanton states $\tilde{\psi}_1$, $\tilde{\psi}_2$, $\tilde{\psi}_3$, etc. $\tilde{\psi}_1$ can be regarded as the state of the quanton with the greatest presence at the point, $\tilde{\psi}_2$ that of the quanton with the second greatest presence, and so forth. In general, the list is indefinitely long, in principle encompassing all quanton instances in the universe, but only finitely many quantons, with some manner of roll-off, have appreciably non-zero presence at any point.

Multi-quanton W-state is a superposition of *pure* states of the form:

$$1 \otimes 2 \otimes 3 \otimes \dots \tag{20}$$

in which individual instances of the quantons are considered distinct and labeled. In the notation of Eq. 20, quanton instance 1 instantiates $\tilde{\psi}_1$, instance 2 instantiates $\tilde{\psi}_2$, and so forth. '$\otimes$' denotes collocation of two or more quantons of the same type.

2.5.2 Tight Superpositions

Pure states serve as building blocks of mathematical expression of multi-quanton W-state. However, only certain types of combinations of pure states, called *tight superpositions*, can represent actual multi-quanton states.

For bosons, tight superpositions are sums of all permutations of a reference pure state, *e.g.*, for $N = 3$:

$$1 \otimes 2 \otimes 3 + 2 \otimes 3 \otimes 1 + 3 \otimes 1 \otimes 2 + 3 \otimes 2 \otimes 1 + 2 \otimes 1 \otimes 3 + 1 \otimes 3 \otimes 2 \tag{21}$$

In Eq. 21, the first term, $1 \otimes 2 \otimes 3$, serves as the reference pure state. For a system of N identical quantons, there are $N!$ pure states equivalent to any reference through a permutation.

For fermions, tight superpositions are the same as in Eq. 21, except that odd-order permutation terms are negated. For $N = 3$:

$$1 \otimes 2 \otimes 3 + 2 \otimes 3 \otimes 1 + 3 \otimes 1 \otimes 2 - 3 \otimes 2 \otimes 1 - 2 \otimes 1 \otimes 3 - 1 \otimes 3 \otimes 2 \tag{22}$$

2.5.3 Spin-Statistics Theorem

It is empirical fact that bosons have integer spin and conform to tight superpositions of the form in Eq. 21, and that fermions have half-integer spin and conform to Eq. 22. The Pauli spin-statistics theorem (PSST) provides theoretical explanation in terms of conventional quantum theory. In terms of the realist framework, PSST relies on the postulate[17]:

$$\boldsymbol{R}(\hat{n}, 2\pi) \cdot (1 \otimes 2 \otimes 3 + 2 \otimes 3 \otimes 1 + 3 \otimes 1 \otimes 2) = \pm(3 \otimes 2 \otimes 1 + 2 \otimes 1 \otimes 3 + 1 \otimes 3 \otimes 2) \tag{23}$$

[17]For this reason, whether PSST can be considered a *theorem* (*i.e.*, a deduction about how nature *must* work) is questionable.

The left-hand side of Eq. 23 signifies the sum of the even-order permutations of a reference pure state, rotated through a full revolution about some arbitrary geometric axis ($\hat{n}$). The right-hand side contains the sum of the odd-order permutations; the + sign (− sign) applies to bosons (fermions).

From Eq. 23, in conjunction with the results for application of the rotation operator to spin states, it follows that rotation of any multi-quanton system through full revolution about any geometric axis reproduces the original W-state, with phase factor +1 for bosons and fermions alike.

To make sense of PSST, multi-quanton W-state can be visualized with analogy to a Möbius strip, in which one side (track A) holds the even-order permutations of the reference state and the other (track B) holds the odd-order permutations (negated for fermions). Under rotation through 2π, track A morphs to track B, and vice versa. Because addition is commutative, the rotated and original states are exactly identical.

It is noteworthy that the concept of even- and odd-order permutations is necessary to make sense of the sign flip for a single isolated fermion rotated through 2π. The even- and odd-order permutations are mutually distinct physically, even if other quantons are nowhere in the physical vicinity.

2.5.4 Fermion Exclusion

The anti-symmetric form of fermion W-state in Eq. 22 has an extremely important implication. If the translational and rotational W-states of any two quantons coincide exactly at some point, the entire multi-quanton state, vanishes at the point, in effect excluding all fermions from the region. If the translational states coincide, the cancellation is avoided only if the two have opposite spin alignments. This is the well-known Pauli Exclusion Principle.

3 Q-2: Physics of Quantum Measurement

3.1 Measurement Events

All of the theoretical development up to this point, which encompasses W-state and is referred to herein as Q-1, has steadfastly ignored measurement processes. This is valid only under the assumption that a quanton interacts with its surroundings only through conservative forces that take effect through a Lagrangian, as in Eq. 8.

3.1.1 Conservative and Non-conservative Forces

In the quantum realm, nature seems to make a dichotomous distinction between conservative and non-conservative forces. Both affect the W-state evolution of quantons, but the two categories are qualitatively distinct and of radically dissimilar natures.

A force is non-conservative if it precipitates a *measurement event*[18], which signifies a local interaction between a quanton and its surroundings that is of a fitful disruptive character, upsetting the smooth predictable evolution of the W-state. Informal analogy to hydrodynamics may be useful: Conservative forces drive smooth evolution of W-state akin to laminar flow, whereas non-conservative forces produce turbulence. The distinction is dynamic and situational in that it has nothing to do with the physical origin (*e.g.*, electromagnetic, strong nuclear) of the force; water is water in either case.

3.1.2 Intractibility of the Measurement Problem

It is thoroughly well-appreciated that the measurement problem is one of the most conceptually intractable issues at the heart of quantum foundations and the one that has most thwarted progress toward deeper understanding. From the outset, quantum theory - and not just the Copenhagen orthodoxy - has been notoriously inconclusive and noncommittal in pinpointing what types of physical processes qualify as measurement events or where/when they occur. What is it about the measurement problem that is so stubbornly intractable, such that measurement events cannot easily be clearly identified and described in ordinary physics terms?

There are at least two answers. One is that wavefunction collapse implies a form of dynamic evolution (Rule 2) that could not be more different from that of the Schrödinger equation (Rule 1). That makes it extremely hard

[18] This designation reflects the pervasiveness of the word *measurement* in quantum physics, which has come to be understood broadly. It really signifies any disruptive process in the microscopic realm - not necessarily resulting from contrived experiment.

to unite and harmonize the two under a single mathematical formalism, to pinpoint exactly where the Schrödinger equation ceases to apply, or to describe departures from it.

The second answer is that wavefunction collapse cannot be squared easily with the strictures of special relativity. It requires a globally coordinated response within the quanton to ensure, for example, that the electron in the two-slit experiment registers a detection at exactly one point on the screen, even though the wavefunction was widely spread out before contact.

3.2 Non-Locality

The work of Bell, followed by the experiments of Clauser and Aspect, has conclusively established that non-locality is an irrefutable fact of nature in the quantum realm. Issues of non-locality, however, were inchoately apparent from the outset. Einstein voiced locality concerns at the 1927 Solvay conference, in connection with wavefunction collapse. Non-locality is manifest in most basic form in wave-particle duality, which is the first confounding phenomenon that crops up in the quantum realm.

No quantum theory of wave propagation by itself can explain wave-particle duality or the mechanics of wave-function collapse. That is as true of Q-1 in the realist framework as it was historically of wave mechanics.

3.2.1 Strong Non-Locality

We begin our foray into non-locality in the setting of Galilean relativity, *i.e.*, special relativity in the limit of $c \to \infty$. Time becomes absolute and decoupled from space.

In the space-time structure of Galilean relativity, it is perfectly tenable to have blatantly non-local forms of physical law, in which the local physical state at point $\underline{x}$, at time $t = 0^+$ (*i.e.*, infinitesimally downstream of $t = 0$), depends on the state at *any other point in space* at time $t = 0^-$, no matter how spatially distant from $\underline{x}$. This is *strong non-locality.* It countenances lateral time travel, but not backwards time travel (which would be vitiated by circular causation logic).

Non-locality is not so easily compatible with the space-time structure of special relativity, for two reasons. First, non-local physical law relies fundamentally on the existence of absolute manifolds, which exist in the space-time structure of Galilean relativity (as constant-time 3D manifolds) but not that of special relativity. Secondly, special relativity, in its strong form, explicitly prohibits faster-than-light signaling.

Quantons are material entities that do have absolute manifolds. Rest manifolds are absolute in that any two observers will agree on their identification.

In principle, it is logically tenable to have strongly non-local physical law within quantons, much like on constant-time manifolds in Galilean relativity. That would be compatible with the weak, but not the strong, form of special relativity.

3.2.2 Weak Non-Locality

The types of non-local effects, such as Bell inequality violations, that actually crop up in the quantum realm and have been witnessed experimentally are more subtle than non-locality of the blatant kind. They exemplify *weak non-locality*, which is compatible with the strong form of special relativity.

Consider the scenario of a quanton, for which Q-1 physical law reigns exclusively everywhere except on a single rest manifold, $\mathcal{M}$. At some or all points on $\mathcal{M}$, the quanton encounters a detector, which is distributed in space-time just like the quanton itself. At each point on $\mathcal{M}$ at which a detector element is encountered, packets are broadcasted and received at other points on $\mathcal{M}$, much like on the constant-time manifold in Galilean relativity. The packets can be thought of, loosely, as distress signals that reverberate throughout the quanton internally.

The lateral (space-like) transfers of packets on $\mathcal{M}$ are all that it takes to realize strong non-locality within quantum (or classical) systems. To prevent faster-than-light signaling[19] imposes strict information-theoretic conditions on the packets and the physical laws governing what happens during measurement events.

[19] *Signaling*, in special relativity, means the conveyance of *information* in the strong sense, *i.e.*, in contradistinction to noise.

3.2.3 Absolute Randomness

The first information-theoretic implication of weak non-locality is that the information *content* of the packets must be purely stochastic (random). Otherwise, a packet could convey information about local conditions at the point on $\mathcal{M}$ from which it originates. It follows that weak non-locality logically requires *absolute randomness*.

3.2.4 Dynamic Implications of Weak Non-Locality

The preclusion of faster-than-light signaling imposes two additional information-theoretic criteria:

- No intervention[20] at any point on $\mathcal{M}$ can exert controllable influence on the W-state evolution at other points on the manifold.
- From (notionally passive) observation of the W-state evolution at some point on $\mathcal{M}$, nothing can be inferred about local conditions elsewhere on the manifold.

From these criteria, it follows that weak non-locality has profound bearing on the fundamental nature of quantum state and the properties and character of physical law that governs its evolution amidst measurement processes.

3.3 Measurement Event Dynamics

How is the evolution of a thread affected by the application of a non-conservative force to the quanton, locally where the thread intersects $\mathcal{M}$? That depends on the answers to two questions: (*i*) Does a measurement event occur at the point of intersection? (*ii*) If so, how is the measurement outcome determined?

3.3.1 Measurement Cross-Section Density

The answer to the first question is determined by the *measurement cross-section density*, *viz.*,

$$\mathcal{Q}(\underset{\rightarrow}{J}, U) \tag{24}$$

which quantifies the degree to which a local portion of the W-state participates[21] in measurement processes that play out on $\mathcal{M}$. It can be thought of as a measurement site density[22]. Integration of $\mathcal{Q}(\underset{\rightarrow}{J}, U)$ over a finite volume on $\mathcal{M}$ yields a finite value, just like the Born Rule.

Eq. 24 indicates that the cross-section density depends on the local W-state through the current density, $\underset{\rightarrow}{J}$. Measurement event occurrence is therefore substantial only where the W-state self-interferes constructively.

U represents the specific nature of the non-conservative interaction between the quanton and its surroundings (*e.g.*, detectors). In the more conventional language of traditional quantum theory, U can be taken to represent a contrived intervention that an experimenter applies to the system under investigation. In general, however, U signifies any non-conservative force that potentially precipitates a measurement event; it can occur in nature or in a science laboratory.

3.3.2 Non-Deterministic W-state Evolution

What happens locally at a measurement site, whereat a thread encounters a detector? In general, the local W-state evolution is governed by a law of the general form:

$$W^{+} = f(W^{-}, U, \nu, P^{-}) \tag{25}$$

in which W^{+} denotes the W-state of the thread immediately after having traversed $\mathcal{M}$. Eq. 25 indicates that the W-state evolution, amidst a measurement process, depends on a combination of deterministic and non-deterministic inputs:

- W^{-} denotes the W-state on the thread immediately before traversal.

[20] Intervention signifies contrived manipulation of a quantum system and necessarily implies application of a non-conservative force.

[21] The *occurrence* of a measurement event is distinct from the measurement *outcome* (*e.g.*, positive or negative detection of a particle).

[22] The notion of measurement sites signifies a discretized representation of the cross-section density, wherein all sites participate equally in a measurement process that occurs globally on $\mathcal{M}$.

- U quantifies the application of any non-conservative force that potentially precipitates a measurement event.
- ν denotes the random content of packets generated locally as a result of non-zero U. Random packet content can be thought of as local rolling of dice. It henceforth goes by the term *innovation*.
- P^- denotes the local P-state, which can be thought of as a bagful of packets that originated on other threads. The packets are notionally "sealed" in that they have been carried passively by the thread and have not yet had any bearing on its W-state evolution.

ν and P^- can be regarded as *hidden variables* - respectively, local and non-local.

In the absence of any local measurement activity, U and ν are notionally zero, and f in Eq. 25 becomes a delta function, signifying deterministic evolution of the W-state locally under a Lagrangian function. P^- is generally non-zero, but it has no effect on the local W-state evolution.

3.3.3 Statistical Form of W-state Dynamics

Consider an ensemble averaging[23] over the local and non-local hidden variable dependence on the right-hand side of Eq. 25. This yields a probability density function (PDF) for W^+, *viz.*,

$$\mathcal{P} = \mathcal{F}(W^-, U) \tag{26}$$

Eq. 26, in conjunction with Eq. 24, can be regarded as the ontic counterpart of the Born Rule, which yields the statistical dependence of the non-deterministic W-state evolution on the pre-measurement W-state (W^-) and the intervention (U).

Consider next the fictional scenario of the approximating local hidden variables theory, wherein the non-local hidden variable dependence in Eq. 25 is suppressed. Ensemble averaging over only the local hidden variable dependence then yields a modified form of Eq. 26, *viz.*,

$$\mathcal{P}_L = \mathcal{F}_L(W^-, U) \tag{27}$$

Weak non-locality requires that Eqs. 26 and Eq. 27 coincide exactly, *viz.*,

$$\mathcal{F}_L = \mathcal{F} \tag{28}$$

Eq. 28 states that the non-deterministic evolution of the W-state, observed only locally at a single measurement site, is statistically indistinguishable from dynamics driven exclusively by local hidden variables. Eq. 28 is a sufficient condition to preclude faster-than-light signaling with respect to the aforementioned information-theoretic criteria.

3.3.4 Quantum Information

The preclusion of faster-than-light signaling applies only to W-state. Lateral exchange of P-state, by contrast, is permitted. It follows that weak non-locality logically implies two types of quantum state that are fundamentally different in their information-theoretic stature. Interaction between quantons and their surroundings involve only exchange of W-state information, whereas P-state information is strictly internal to quantons.

3.4 Measurement Outcome Correlations

Under weak non-locality, it is possible to realize, within single quantons or systems of mutually entangled quantons, strong correlations among measurement outcomes that cannot be explained by any local hidden variables theory. A mechanistic model of how non-local hidden variables can produce strong correlations is proposed in this section.

[23] In the context of absolute randomness, ensemble averages have absolute physical significance (unlike in classical statistical mechanics, where they are approximations owing to lack of knowledge of exact conditions).

3.4.1 Multiple Measurement Sites

We continue with the scenario of a quanton, for which Q-1 physical law reigns exclusively everywhere except on a single rest manifold, $\mathcal{M}$. In this simplified scenario, the P-state at each point on $\mathcal{M}$ contains only packets originating from other points on $\mathcal{M}$.

Suppose that there are finitely many (N) measurement events at different points on $\mathcal{M}$, whereat the quanton locally encounters detector elements. For simplicity, assume univariate local measurement outcome spaces at each site, meaning that the measurement outcome (W_n^+) at the n'th site is mappable to a single number, μ_n.

The measurement outcomes collectively conform to a statistical distribution represented by an N-dimensional PDF, *viz.*,

$$P(\mu_1, \mu_2, \ldots, \mu_N) \tag{29}$$

which is normalized:

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\cdots\int_{-\infty}^{\infty} P(\mu_1', \mu_2', \ldots, \mu_N')\, d\mu_N' \cdots d\mu_2'\, d\mu_1' = 1 \tag{30}$$

All statistical properties (ensemble averages) of the measurement outcomes are derivable from the PDF. Ensemble instances differ only in particular random values in the packets generated at the sites. The functional form of P in Eq. 29 depends on the local conditions (W^- and U) at each measurement site.

In a local hidden variables theory, the PDF decouples, *viz.*,

$$P(\mu_1, \mu_2, \ldots, \mu_N) = P(\mu_1)P(\mu_2)\cdots P(\mu_N) \tag{31}$$

That the PDF, in general, does not decouple reflects the particle-like essence of quantons, which measurement processes conserve.

3.4.2 Decentralized Innovation and Arbitration

The purpose of the mechanistic model is to demonstrate, from a purely information-theoretic standpoint, how strong measurement outcome correlations can be realized within the strictures on weak non-locality. The objective is to explain (*i*) what has to happen in individual systems to produce outcomes that conform to the ensemble PDF, and (*ii*) how those requirements can be met and implemented.

For the purpose of describing the mechanism, the local presence of the quanton, at each measurement site, is portrayed in fictional terms of a computing agent. A story will be told of how the agents operate in decentralized fashion, but use information globally exchanged with one another on $\mathcal{M}$ and cooperate to produce measurement outcomes that conform statistically to P.

The story synoposis is as follows:

- When the quanton locally encounters a detector element, the computing agent at the measurement site generates a packet with purely random information content. It broadcasts the packet on $\mathcal{M}$.
- Global information exchange transpires on $\mathcal{M}$. Each agent receives packets from all others.
- Each agent has knowledge of P, which can be regarded as a table published globally on $\mathcal{M}$. Each agent consults the table, in conjunction with its own innovation and that of the others, to generate its own local measurement outcome (μ).

3.4.3 Innovation Components

In the mechanistic model, the packet innovations are means to the end of generating the measurement outcomes. Conceptually, this is no different from what a conventional computer does to generate a normally distributed random number (x) from a random number (r) uniformly distributed on the unit interval. It solves for x such that the definite integral under the Gaussian curve to the left of x equals r.

To generalize the procedure to a multivariate PDF of N dimensions, one requires N uniformly distributed numbers ($r_1, \ldots, r_N$), along with a specified order in which the dimensions will be indexed. In the first step, x_1 is computed such that the N-dimensional hypervolume to the left of x equals r_1. In the second step, x_2 is computed based on the $(N-1)$-dimensional hypervolume corresponding to the PDF slice conditioned on x_1. And so forth.

To implement the procedure in a decentralized setting, the agents must agree upon a prioritization of the measurement sites. The process through which agreement is forged is called *gambit arbitration*. It is simple to implement. Each agent generates an innovation component called a *gambit*, which is a random number uniformly distributed on the unit interval[24]. From the global information exchange on $\mathcal{M}$, each agent ascertains its rank in the lineup by comparing its own gambit to those of the other agents.

The aforementioned $r_1, \ldots, r_N$ are each generated separately by the agents. It therefore suffices for each packet to contain two random numbers: gambit (γ) and index (r).

3.4.4 Measurement Outcome Computation

After gambit arbitration, the agents perform a sequence of definite integral evaluations to derive the measurement outcomes:

- The highest-ranking thread selects μ_1, *viz.*,

$$\int_{-\infty}^{\mu_1} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} P(\mu_1', \mu_2', \ldots, \mu_N')\, d\mu_N' \cdots d\mu_2'\, d\mu_1' = r_1 \tag{32}$$

- The second highest-ranking thread selects μ_2, *viz.*,

$$\int_{-\infty}^{\mu_2} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} P(\mu_1, \mu_2', \ldots, \mu_N')\, d\mu_N' \cdots d\mu_3'\, d\mu_2' = r_2 \tag{33}$$

  in which μ_1 is the value selected in the first step.

- The third highest-ranking thread selects μ_3, *viz.*,

$$\int_{-\infty}^{\mu_3} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} P(\mu_1, \mu_2, \mu_3', \ldots, \mu_N')\, d\mu_N' \cdots\, d\mu_3' = r_3 \tag{34}$$

- $\ldots$

- The lowest-ranking thread selects μ_N, *viz.*,

$$\int_{-\infty}^{\mu_N} P(\mu_1, \ldots, \mu_{N-1}, \mu_N')\, d\mu_N' = r_N \tag{35}$$

3.4.5 Natural Computation

The mechanistic model has now been described in full. It is an outline of *how* nature, in principle from a purely information-theoretic standpoint, can operate within the strictures on weak non-locality to implement measurement outcome correlations.

Natural computation is a pretentious term, but it is really a metaphor for what nature has to do to produce measurement outcomes in individual systems that conform statistically to a specific PDF. Eqs. 32-35 appear complicated, but they are no more so than what nature has to do to implement the Born Rule of conventional quantum theory. Natural computation connotes - and expresses marvel at - that nature somehow implements the Born Rule and Bell inequality violations without human computing technology.

The mechanistic model posits multiple computing agents because we naturally think of space as a barrier separating them. In natural computation, however, space does not act as a barrier.

3.5 Entanglement

3.5.1 Entangled Quanton Pairs - Double Measurements

The theoretical analyses of Einstein-Podolsky-Rosen (EPR) and Bell, followed by the experiments of Clauser and Aspect, involved measurements on pairs of entangled photons that emanated from a common origin but departed

[24] Gambit arbitration is conceptually no different from what CSMA/CD does to mitigate network traffic collisions.

in opposite directions. There are essentially just two threads, both of which encounter detectors. It is always the case that one photon registers with polarization up and the other registers polarization down[25]. These tests are an application of the preceding analysis for $N = 2$ measurement sites.

The realist account of what happens is as follows. Upon encountering the detectors, each photon[26] generates a gambit-index pair. The photon drawing the highest gambit gets first crack to choose whether it registers polarization up or polarization down. The other photon is constrained to produce the opposite polarization.

3.5.2 Entangled Quanton Pairs - Single Measurements

Suppose that just one of the photons (A) encounters a detector, while the other (B) continues on and is not subjected to measurement until a later time.

On the rest manifold ($\mathcal{M}$) intersecting the detection site, only A generates a packet. The gambit (γ) in that packet prevails by default. The index value (r) in the packet determines whether A registers polarization up or polarization down.

Either way, B acquires an *entanglement obligation* to produce the opposite polarization when it is eventually measured. To account for the obligation, the state of B must change discontinuously on $\mathcal{M}$. It is not the W-state that changes, but a supplemental form of local quantum state called P-state.

This is actually the scenario that more generally represents the dual detection experiments, since the detections almost never occur exactly simultaneously (*i.e.*, with one rest manifold intersecting the measurement events at both sites). P-state ensures that the deferred measurement outcome for the second photon is the same as it would have been had the detections been simultaneous.

3.5.3 P-state

P-state gives expression to entanglement obligations in the form of supplemental quantum state. In the realist view, entanglement obligations are inferred through natural computing that draws upon global information exchange on rest manifolds on which partial measurement of some form occurs. In terms of conventional quantum theory, the equivalent occurs in the application of a projection operator to effect change in the epistemic wavefunction.

The realist framework affirms that spooky action at a distance, in the sense expressed by Einstein, is real; the state of B really does change as a result of an act of observation[27] elsewhere. Observation creates (but does not *control*) reality in that it affects W-state evolution, both locally and remotely.

3.5.4 Wavefunction Collapse - Full Detection

The realist explanation of the dual detection experiments equally well describes the fates of threads within a single quanton. During flight (*e.g.*, when an electron transits through the apparatus of the two-slit experiment), the threads fan out spatially. In a full detection scenario, the quanton encounters a wide detector that completely intercepts the fan-out area. It is then always that exactly one thread registers a positive detection event, whilst the others register negative. Wavefunction collapse is effected, and the quanton appears at only one measurement site as a concentrated[28] particle.

What becomes of the W-state at the positive and negative detection sites? At the negative detection sites, the W-state simply dies. The surroundings learn nothing[29], and the quanton ceases to have any ontic presence beyond the detector at the non-measurement sites. At the positive detection site, the W-state gets "promoted", and the intensification becomes manifest to the surroundings. It follows that W-state dynamics, amidst measurement events, are globally, but not locally, conservative.

3.5.5 Wavefunction Collapse - Partial Detection

In a partial detection scenario, the quanton encounters a narrower detector that only partially intercepts the fan-out area. There are then two possible outcomes. One is that a positive detection occurs. The W-state is

[25] This is the Aspect experiment for the case of aligned polarization axes in the detectors ($\theta = 0$).
[26] More correctly, the natural computing agent representing the entangled photon pair at the measurement site.
[27] Observation in the active quantum sense. It is synonymous with what has herein been called intervention.
[28] Not exactly a *point* particle, but of a size several orders of magnitude smaller then the pre-measurement wavefunction spread.
[29] Epistemically, non-detection is non-acquisition of information from the quanton.

promoted at the positive detection site, but dies everywhere else on the detector surface. The W-state on threads not intercepted by the detector continue on undisturbed, but they effectively become neutered by the P-state. The P-state guarantees that they will never register positive; they become *ghost waves*.

The other outcome is that no detection occurs. The W-state dies at all points on the detector surface[30]. The W-state on threads not intercepted by the detector continue on undisturbed, but the P-state renders them more potent. When the surviving W-state eventually encounters a full detector, a positive detection is certain to occur.

In both cases, the discontinuous change in P-state on the surviving threads has a strengthening or weakening effect, not on the W-state *per se* but on the forecasting odds of positive detection when the surviving W-state is eventually subjected to measurement. In this way, P-state absorbs quantum Bayesianism (QBism) into the realist framework.

3.5.6 P-state Evolution Between Measurement Events

P-state has been described thus far only in terms of its impact on measurement outcomes. Between measurement events, P-state is carried passively by threads. It has no bearing on W-state evolution until measurement events actually occur.

Quantons become entangled with one another if their W-states interact significantly at any time between measurement events. Their rest manifolds become conjoined, and their P-states become commingled and evolve in tandem. Entanglement can arise owing to common genesis (*e.g.*, the photon pairs in the Aspect experiment) or coming into contact (*e.g.*, two electrons that were originally separate, but each allowed to diffuse into a box enclosure). Once entangled, the quantons remain entangled until the next measurement event, even if they become spatially separated and cease to interact.

3.6 Measurement Processes

Q-2, as developed thus far, demonstrates that - and how - Rules 1 and 2 can coexist within a single theoretical framework. Measurement events occur at definite space-time points and play out in spatio-temporally distributed fashion under the strictures of weak non-locality. It follows that they can be regarded as perfectly ordinary physical processes; quantum measurement is demystified. However, Q-2 does not, by itself, conclusively answer questions of what kinds of physical processes constitute measurement events.

3.6.1 Externally Triggered Measurement Events

The only types of measurement events that have been mentioned thus far involve abrupt collisions between a quanton and a detector, which is typically assumed to be a macroscopic device. To the quanton, these are externally triggered events that force an all-or-nothing response. Either a positive or a negative detection outcome occurs locally at any point on the detector surface. If the detector surface completely intercepts the fan-out area, a positive outcome occurs at exactly one local site.

Measurement events of this kind are unambiguous. There is no doubt that they really do provoke sudden departure from the smooth deterministic evolution that had been taking place before the encounter. They are the best "understood" forms of measurement because they were the focus of traditional quantum theory and are most closely associated with experimentation.

Historically, it has been extremely difficult to pinpoint the physical nature of measurement events. The Copenhagen dispensation was notoriously noncommittal on the subject, and the quantum dissidents were little better [4]. That legacy has left a spectrum of ideas on what constitutes quantum measurement:

- The narrowest and most extreme view holds that consciousness plays an essential role in what constitutes a definitive act of measurement. Taken seriously, it implies that quantum physics, as an all-encompassing theory of principle governing the universe, could not exist as such until human brains evolved into existence on Earth.

- The traditional view of quantum measurement holds that it involves contrived experimental intervention, in which an experimenter asks a certain question of nature in a well-defined setting using macroscopic

[30] This is known as a Renninger negative-result event. [5].

instrumentation. Analysis of this scenario is aided by the simplifying assumption of the *Heisenberg cut*, which holds that the quantumness of the measurement apparatus can, for all practical purposes, be ignored since it is so much larger than the quantum system being investigated. This view of measurement can serve as a practical tool for predicting outcomes of experiments, but it cannot stand as a general theory of nature.

- *Decoherence* represents a much more general view of measurement. In nature, quantum systems of all sizes are continually buffeted by interactions with their surroundings. Those interactions are fitful and disruptive, causing the W-state to lose its interesting quantum features (*i.e.*, interference effects) and preventing it from straying far from classical behavior. Decoherence effects readily explain why quantumness is almost never manifest at macroscopic scales[31]. This view of measurement, unlike the preceding two, does not depend on the existence of physics laboratories or physicists.

In the realist framework, the decoherence view identifies, reasonably comprehensively, the essential nature of *externally triggered* measurement events. They arise through natural interventions of origin extrinsic to the quanton of interest.

3.6.2 Internally Triggered Measurement Events

A less trodden avenue of exploration is the notion of *internally triggered* "measurement" events, wherein the W-state of a quanton changes non-deterministically, but not because of interaction with surroundings. For all practical purposes, they are indistinguishable from externally triggered measurement events in terms of their impact on W- and P-state dynamics within the quanton.

Internally triggered measurement events, in principle, can conceivably arise from instability within the W-state. Simple examples include: (*i*) spontaneous emission from excited atomic electron states, (*ii*) radioactive decay of nuclei, and (*iii*) tunneling phenomena. They can also arise completely spontaneously in stable W-states, including scenarios as basic as free quanton motion.

3.6.3 Wavepacket Expansion or Random Walk?

We return to the scenario of wavepacket expansion in Eq. 15. Imagine that we conduct an experiment, in which quantons effuse out of a narrow hole at $x = 0$ and transit through the apparatus, unimpeded and undisturbed, forward in the $+\hat{y}$ direction until they bang into a detection screen. The statistical distribution of detection points, after a large ensemble of individual runs has been performed, is analyzed and found to be normally distributed.

The realist framework can accommodate two ways of explaining the results:

- **Model I**: This model holds that the W-state actually does evolve deterministically during transit from the source hole to the screen. It can be represented, in very simplified form, by a linear growth model[32] for the variance, *viz.*,

$$\sigma^2(t) = \sigma_0^2 + \hbar t/m \tag{36}$$

  in which σ_0^2 is the W-state width variance at the hole, m is the quanton mass, and t is the transit time through the apparatus (assumed, for simplicitly, to be constant). Statistical analysis of the experimental data confirms quantitative agreement with the theoretical prediction of Eq. 36.

- **Model II**: This model envisages a very different physical picture of what goes on with the W-state dynamics and evolution during the transit period. Far from evolving deterministically and unmolested, the quanton is continually buffeted by *micro-measurement* events, which occur spontaneously, including possibly even under ideal conditions in vacuum at absolute zero temperature. Following any micro-measurement, the W-state width is pinched down to the Compton wavelength (or possibly some larger value), and the quanton gets a little kick to the left or right. The cumulative effect of the micro-measurements is to cause the quanton to execute a random walk in the transverse (x) direction. The random walk results in linear variance growth and produces agreement with Eq. 36.

[31] Except in highly rarefied experiments that produce mesoscopic quantum states.

[32] This is actually a fictional departure from the wavepacket expansion result in Eq. 15 in that it ignores the complicating effect of transverse velocity uncertainty.

The two models yield identical predictions of the experimental results, and both are formulated within the realist framework. However, they tell radically different theoretical tales of what happens behind the phenomenology. They agree in their identification of the externally triggered measurement events, which is not a topic of doubt, but they disagree on whether internally triggered measurement events occur.

The first question would be whether there could be devised a different experiment that could decide between the two models. Such an experiment, in essence, would have to manipulate the W-state of Model I and cause it to exhibit some interesting interference effect. No such effect could be achieved with the W-state of Model II, since the micro-measurements keep it suspended in a nearly classical state.

3.6.4 Spontaneous Emission

Excited atomic electron states are usually meta-stable and short-lived. The excited electron quickly drops back down to the ground state, emitting one or more photons in the process. Quantum mechanics only predicts mean longevities of the excited states (expressed as transition rates), along with selection rules prescribing the hops[33] down to the ground state. It does not offer any further insight or detail on what precipitates the transition, how it unfolds dynamically as a spatio-temporally distributed process within the confines of the electron cloud, the state of the photon when it departs from the atom, or the cast of measurement events.

The following account is a sample sketch of how the realist framework would describe an occurrence of spontaneous emission in an individual atom:

- The W-state of the excited electron is continually subjected to internally triggered measurement events, which can be thought of as analogous to genetic mutations in biological populations. Some of these are sensitive to - and gain marginal advantage from - stability differences that make W-state conditions in the next hop more favorable.

- Many locally favorable mutations occur. Unlike in ecology, however, they enjoy global coordination through P-state dynamics. A widespread collection of mutations quickly takes root and snowballs coherently. The W-state globally morphs into that of the next hop state.

- The globally coordinated metamorphosis of the electronic W-state is an objectively real physical process that transpires in the individual atom *when nobody is looking*. It is characterized by a (fuzzy) time of onset and a duration (transition width).

- During the transition, a nascent photon begins to take shape. The photon is a form of W-state associated with an electromagnetic potential, $(\boldsymbol{A}, \phi/c)$, and spin. The photon emanates from the atom as a spherically symmetric shell of W-state potential. It remains such as long as the photon is in free transit.

- Upon encountering one or more "detectors" anywhere[34], at most one positive detection event occurs. Positive detection precipitates a corpuscular response at the detection site, whereat the promoted W-state has discrete energy $E = \hbar\omega$ equal to the energy difference between the two electronic states.

- If a positive detection does occur, the photonic W-state instantaneously collapses and dies in globally coordinated fashion everywhere else on the shell.

- If no positive detection occurs, the negative detections alter the course of the W-state from its original spherically symmetric form. P-state rearrangement ensures that the altered photonic state will eventually register a positive detection when it becomes subjected to measurement encounters with other detectors.

Similar accounts would describe tunneling phenomena and radioactive decay of nuclei. In all of these scenarios, instability of the original W-state results in a dramatic metamorphosis of the W-state. It is an objectively real transformation that is driven entirely by internally triggered measurement events.

[33] A *hop* signifies a pair of states that are radiatively coupled directly to one another, according to the selection rules.

[34] This is in the sense of decoherence, in which *detector* means any physical object that can absorb the photon.

3.6.5 Time-Dependent Perturbation Theory

Quantum mechanics calculates transition rates for spontaneous emission by appealing to time-dependent perturbation theory (TDPT), which is an extension of the wave mechanics technique of forming static combinations of pure wave components to satisfy stipulated boundary conditions. In TDPT, a time-varying perturbation term is added to a time-invariant baseline Hamiltonian, and the wavefunction solution is expressed as a linear combination of the baseline eigenstates with time-varying coefficients.

The mathematical formalism of TDPT is couched entirely in terms of Rule 1, and the resulting solution is ostensibly an uncollapsed wavefunction. However, the conventional treatment then goes on to speak of transition rates as probabilities per unit time. The well-known Fermi Golden Rule derives the probabilities by applying the Born Rule to the uncollapsed wavefunction.

Wavefunction solutions of time-invariant Schrödinger equations are long-lived and can wait until eventual measurement events before the Born Rule need be applied. Not so with solutions of time-dependent Schrödinger equations; quantum mechanics is only able to make practical use of them by applying the Born Rule shortly after the Hamiltonian perturbation begins to take effect. Rule 2 physics becomes inextricably drawn into the picture, even though the Hamiltonian formalism is intended to be Rule 1 only. TDPT tries to introduce a disruptive non-conservative force, but quantum mechanics provides no natural way of doing so because it is too inflexible to depart from the Hamiltonian formulation of the Schrödinger equation.

4 Realist Framework vis-à-vis Other Interpretations

Various interpretations of quantum mechanics that have been proposed over the decades. *Interpretation*, however, is a misnomer; they are really different physical *theories*. They all attempt to explain how and why quantum mechanics works, but they go about filling in the details differently. Several, but by no means comprehensively all, are discussed in this section.

4.1 Pilot Wave Theory

The central contention of pilot wave theory [7] - first proposed by de Broglie in the late 1920's and later developed by Bohm (1952) - is that the electron ontology is primarily that of a classical point particle. The pilot wave is essentially an elaborate force law that can reproduce the interference pattern in the two-slit experiment. Whereas the new framework posits a combination of W-state and P-state, Bohm took the conjunction of wave and particle literally.

4.1.1 Pilot Wave Theory - Force Law

The conceptual simplicity of pilot wave theory comes at the price of complicated requirements on the force field. It is first noted that an interference pattern is much more elaborate than spatial arrival distributions resulting from simple familiar types of classical force laws, such as Coulomb attraction of the electron to the lensing wire. Conversely interpreted, it takes a complicated force law to produce the interference pattern. While that does not violate any fundamental tenets of classical physics, it begs the question of the physical origin of such a force field. Is it of electromagnetic origin or related to the specific nature of the experimental configuration (e.g., materials used)? That seems improbable, since the lensing effect can be achieved by many experimental configurations and techniques. They span a diverse range of underlying physical principles (*e.g.*, at one extreme, gravitational lensing) and can employ a wide variety of particles other than electrons, including small and large molecules, which are electrically neutral. In all cases, interference phenomena can be produced under the right conditions.

The interference pattern exhibits a quantitative feature that is of universal character. The spacing between interference fringes is characterized by a wavenumber parameter, k, that is directly proportional to the particle momentum, p, measured at the detection site, as in Eq. 11b. Planck's constant, $\hbar$, surfaces in all realizations of the two-slit experiment.

In the classical pilot wave framework, any physical theory of the force field must account not only qualitatively for the existence of interference phenomena but also quantitatively for the relationship in Eq. 11b. It must incorporate $\hbar$ integrally into the mathematical fabric of the theory. Furthermore, in the limit of $\hbar \to 0$, it must reduce to the conventional classical physics describing the lensing mechanism and the experimental configuration.

It therefore splinters into a diverse multitude of separate classical theories, each accounting for one of many techniques of implementing the two-slit experiment. All of these must be *quantized* (*i.e.*, generalized to non-zero $\hbar$) in a way that accounts both qualitatively and quantitatively for the interference phenomena.

4.1.2 Assessment of Pilot Wave Theory

The splintering frustrates the quest for a simple unified explanation of the central phenomenon exhibited in all implementations the two-slit experiment.

The realist formulation departs from Bohmian mechanics in that it rejects the hypothesis of a particle-like electron ontology. It instead posits an ontology that is *primarily* wave-like. In this view, the electron *is* spread out spatially during its journey through the apparatus and passes through both slits, as opposed to one or the other. The interference phenomenon is no longer regarded as the result of a force field extrinsic to the electron, but instead, as interference of the electron with itself. In this respect, the realist formulation is closer to the conventional wavefunction-based tale of what happens than to Bohm.

With a wave-like ontology, the force field can be modeled in simple conventional form. The interference pattern naturally emerges, and there is no need for modification or fusion of the classical theories of the force fields.

Bohmian mechanics is sometimes regarded as synonymous with non-local hidden variables theory. The realist formulation also embraces non-local hidden variables, but in an entirely different form from what Bohm proposed. The concept of P-state handles non-locality more naturally and ably than the Bohm theory.

4.2 Many Worlds

4.2.1 Primacy of the Wavefunction

The central contention of Many Worlds - first developed by Everett (1957) and later championed and popularized by DeWitt - is that quantum theory can be formulated entirely in terms of Rule 1. The realist framework[35] concurs with Many Worlds that the dynamics of quantum state evolution is predominantly wave-like, that Rule 1 physical law is important in its own right, and that all objects large and small can be described in terms of wavefunctions. Everett deserves historical credit for advancing the idea that the wavefunction itself is ontically real; the realist framework differs only on the matter of W-state versus the wavefunction *per se*.

4.2.2 Denialist Stance on Measurement

Many Worlds waives away the complications of the measurement problem through the explanation that the wavefunction branches[36] of the observer and observed system become mutually entangled. The apparent result of just one observed outcome corresponds to a particular pairing of the two branches; the pairing comprises a term in a stupendously complicated universal wavefunction.

The realist framework wholly disagrees with Many Worlds on its sweeping rejection of Rule 2 and its denialist stance on quantum measurement. Many Worlds fails to explain the phenomenological reality of the one universe in which the whole of physics, as far as we will ever be able to tell, actually lives.

Furthermore, Rule 1 physics, as conventionally formulated (and accepted by Everett), is plagued by difficulties and contradictions vis-à-vis measurement issues. Many Worlds and TDPT both strive to be Rule 1 only, but in practice, they are forced to invoke the Born Rule (or what is essentially the same, in selecting one wavefunction branch pairing over others) in an expedient manner.

4.2.3 Many Worlds Complexity

Many Worlds makes no pretense of complexity control. It pitches the notion of a universal wavefunction, but says nothing about how science would ever be able to construct or make use of a practical working representation of it. The realist framework, by contrast, addresses the complexity issue directly in the treatment of multi-quanton systems, in which a roll-off concept is introduced. Only the finitely many quantons with appreciable spatial presence in any region of space-time figure consequentially in Rule 1 physics.

[35] Many Worlds also claims to be realist, but only in a narrowly technical sense.

[36] Since Many Worlds posits a universal wavefunction, the here-and-now universe must be described in terms of wavefunction branches.

The realist framework maintains that physics can be kept simple, with Rules 1 and 2 coexisting in one three-dimensional world of the familiar kind.

4.3 Objective Collapse Theories

Objective collapse signifies a class of theories that posit that wavefunction collapse in microscopic systems is an objectively real physical process. The best known of these is Continuous Spontaneous Localization (CSL), which is a fusion of the work of Pearle with that of Ghirardi, Rimini, and Weber (GRW).

4.3.1 Coexistence of Rules 1 and 2

The realist framework is sympathetic with the motivations of objective collapse research. It takes the view that Rules 1 and 2 coexist and must be harmonized in a single theoretical framework. Unlike Copenhagen and Many Worlds, objective collapse takes Rule 2 physics seriously. It is also the only well-known alternative approach that embraces the concept of micro-measurements. CSL modifies standard quantum theory to accommodate spontaneous micro-measurement events, which are characterized by a certain probability, per unit time per unit spatial volume, of collapse precipitation.

4.3.2 Micro-Measurement Model Detail

The realist framework and CSL appear to think alike on the importance of Rule 2 and micro-measurement as a key concept, but not necessarily on details. Outstanding questions include: (*i*) tuning of the model parameters and their sensitivities to environmental conditions, (*ii*) dependence of the model formulations on premises (*e.g.*, rooted in wave mechanics) that might be unduly rigid, and (*iii*) how easily the models square with causal strictures such as weak non-locality.

4.4 Copenhagen

Copenhagen needs no introduction. In favor of standard quantum theory is the fact that it has unfailingly proved *correct*, despite its being inscrutable. It is also reasonably simple and parsimonious. Otherwise, it seems improbable that the founders would have zeroed in so quickly on a correct and durable set of cookbook rules, all in the space of a few years [11].

4.4.1 Schrödinger's Cat

Copenhagen takes a minimalist view as to what constitutes a measurement event[37]. It recognizes only forms of contrived intervention involving macroscopic instrumentation in well-defined experimental settings. A problem with that, of course, is that it leaves vague how quantum physics plays out in the natural world, removed from physics laboratories and physicists.

Schrödinger's cat is an extreme implication of the noncommittal stance on what qualifies as measurement. The riddle of the cat implies a sweeping rejection of decoherence and any triggers of physical collapse aside from the human act of opening the box. The realist formulation takes the view that the cat is either dead or alive inside the unopened box, with no middle ground of superposition realistically achievable.

4.4.2 HUP and Wavefunction Collapse

HUP implies that the spatial width, Δx, of a quanton cannot be pinched down to the Compton wavelength ($\hbar/mc$), let alone zero, without causing the quanton to flit away at the speed of light. Yet compressing Δx to zero is exactly what is alleged to happen in wavefunction collapse, when the quanton is detected *at* a definite position. This blatant contradiction - or lack of linguistic clarity - is seldom acknowledged or explained in mainstream discourse.

[37] In Copenhagen parlance, it is technically not correct even to speak of a measurement *event*, as that implies something well-localized.

4.4.3 Dogmatic Anti-Realism

If the conceptual intractability of quantum physics seems any less now, it is only because we have had a whole century to think about it. The 1920's, however, did not have the benefit of the experimental and theoretical insights that have immensely illuminated our 21st-century understanding. The founders did not have good answers to the hard foundational questions, and the historical result was that anti-realist sentiment took root and became the dominant way of thinking in 20th-century physics. Practitioners had a bag of tools that worked, and they followed the path of least resistance, which in truth was the only known viable path forward at the time (and for the most part still is).

Under Bohr and Rosenfeld, anti-realism hardened into an explicitly obscurantist dispensation that actively discourages and shuns inquiry that seeks to understand quantum mechanics more deeply than the fact that it works as a practical tool to predict outcome probabilities in experiments. The anti-philosophical stance maintains that it is altogether futile and meaningless, as a matter of fundamental principle, to seek clarity and understanding on basic questions of what, where, when, and how.

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