A New Foundation for Standard Quantum Theory: Extension to Electrodynamics

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Abstract

This paper builds upon https://vixra.org/abs/2402.0149 and https://vixra.org/abs/2406.0113, which proposed a novel realist framework for making sense of standard quantum theory. The framework is said to be "realist" in that it provides a complete observerless picture of quantum state ontology and dynamics, in conjunction with a mechanistic account of measurement processes, that answers basic questions of what, where, when, and how.

The framework embodies a general quantum ontology consisting of two entities, called W-state and P-state, that respectively account for the wave- and particle-like aspects of quantum systems. 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 is a non-local hidden variable that constrains the probability distributions governing deferred measurement outcomes, such as in the Einstein-Podolsky-Rosen (EPR) thought experiment. The framework features a full solution of the core measurement problem, which pertains to the global coordination within quantum systems required to bring about wavefunction collapse in causal fashion consistent with special relativity.

The extent of development in those preceding papers amounts essentially to a quantum theory of matter particles. In this paper, it is shown how the realist quantum-theoretic framework for particles can be extended to encompass electromagnetic fields. The paper elaborates upon the implications for quantum gravity and how other interpretations (*e.g.*, Many Worlds, GRW) deepen understanding of the realist framework.

Contents

1 Introduction

Two preceding papers [15, 16] by this author proposed a realist formulation of quantum theory for matter particles. The reader is referred to those for fuller explanation and technical detail. A summary outline of the main ideas is provided below.

- **Quantum state**
  - **W-state**: This is the wave-like part of quantum state. It is an ontic generalization of the wavefunction.
  - **P-state**: This is the particle-like part of quantum state. It is a realization of non-local hidden variables, which enforce strong correlations[1], conservation law constraints (*e.g.*, such as in EPR), and the holistic oneness of particles.
- **Structure of W-state**
  - **Quantum wave elements**: W-state consists of superpositions of quantum waves writ small [15], *viz.*,

$$\psi(\underset{\rightarrow}{x}) = \int \tilde{\psi}(\underset{\rightarrow}{k}, \underset{\rightarrow}{x}) e^{i(\underset{\rightarrow}{k} \cdot \underset{\rightarrow}{x})} \, d\underset{\rightarrow}{k} \tag{1}$$

    The Fourier terms on the right-hand side of Eq. 1 represent quantum wave elements locally tangent to the W-state. In the realist framework, the quantum wave elements are ontically primary and distinctively non-classical. Unlike classical waves, they have no crests, troughs, or zeros. Their ontology is inherently such that only phase differences between state values at different points are meaningful.
  - **Superposition**: The realist framework recognizes two forms of superposition. *Distributed superposition* is the simple fact of the W-state being spatially spread out like a wave. The particle is in multiple places at once, and Q-1 dynamics (see below) always keep it that way[2]. *Local superposition*, expressed in Eq. 1, is the coexistence of multiple velocities[3] at a single point in space-time.
  - **Threads**: Quantum wave elements extend along curvilinear paths called *threads*. The path geometries and phase variation along the paths are driven by Q-1 dynamics. In the quantum theory of particles, threads determine causal relationships amongst quantum wave elements at time-like separated points.
  - **Spin**: Spin is anisotropy inherent in any fermionic quantum wave element, which, in its rest frame, has a certain (objectively real) directional alignment in three-dimensional space.
  - **Identical particle interchange**: Multiple particles of the same kind can be locally superposed. The W-state consists of fermionic or bosonic *tight superpositions*. For fermions, the exclusion principle takes effect at the thread level: no more than one fermion can have a given combination of velocity and spin alignment at a given point.
  - **Roll-off**: This is an information-theoretic complexity control principle for W-state, including tight superpositions and entanglements. For all practical purposes, it enables relevant aspects of the wavefunction of the universe to be described compactly, with a finite amount of information.
- **Solution of the core measurement problem**
  - **Rest manifolds**: These are a key emergent feature of W-state. They furnish an invariant definition of proper time within quantum systems as a whole and amount to a built-in ether within W-state that is compatible with special relativity.
  - **Weak non-locality**: This is an information- and control-theoretic conception of how non-local quantum effects can be realized within the space-time structure of relativity, in such a way that superluminal signaling is precluded in two specific respects: (*i*) *Information* about the occurrence of a measurement event cannot be conveyed to any remote point on the rest manifold. (*ii*) The contrived occurrence of a measurement event cannot exert *controllable* influence on what happens elsewhere on the manifold. The preclusion of superluminal signaling logically requires absolute randomness spawned at local measurement sites.

[1]In quantum theory, *strong correlations* are ones that violate the Bell inequalities.
[2]That the W-state is spatially distributed in the first place is the qualitative essence of the uncertainty principle.
[3]Actually, combinations of velocity and spin orientation.

- **Tripartite structure of quantum theory**
  - **Q-1**: This encompasses the smooth deterministic evolution of W-state in the absence of measurement events. It is the realist generalization of the Schrödinger and Dirac equations. Q-1 dynamics are mostly local, but with some notable counter-examples, such as manifest in the Aharonov-Bohm effect.
  - **Q-2**: This encompasses all forms of non-deterministic dynamics that are "spontaneous", *i.e.*, occur in the absence of contrived experimental intervention. It includes well-known phenomenology such as radioactive decay and spontaneous emission. It also includes concepts of physical wavefunction collapse, such as envisaged in GRW. The realist framework holds that Nature, in the absence of observers, in the microdomain is a continual interplay of Q-1 and Q-2 dynamics. The former tends to expand the spatial extent of W-state and props up the uncertainty principle, whereas the latter tends to narrow the W-state and prevent it from straying far from classical behavior.
  - **Q-3**: This encompasses "measurement" in the sense of traditional quantum theory. It is the special case of well-defined measurement processes concentrated on a single rest manifold. The W-state can then change discontinuously in globally coordinated fashion across the entire manifold. In other words, a quantum jump, much as Bohr originally envisaged.

2 Contributions of Existing Interpretations to the Realist Framework

This section elaborates upon the well-known interpretations[4] of quantum theory and how they contribute to understanding of the realist framework. It offers new thoughts that were not in the previous papers.

2.1 Realism

Feynman famously said that nobody understands quantum mechanics and that the two-slit experiment quintessentially exemplifies what makes it enigmatic and conceptually intractable. Quantum mechanics, as it has been understood for the last century, is unable to answer basic story-telling questions of what, where, when, and how. Those questions are closely interwoven with the core measurement problem, which was addressed in the preceding papers.

Realism, throughout this and the preceding papers, has a straightforward definition: a physical theory that regards the basic questions as meaningful and provides answers. Unfortunately, realism, in conventional discourse on quantum foundations, is often understood to have a much narrower meaning, which holds that realist theories can only deal with ordinary objects. An *ordinary object* has a full complement of dynamic attributes, which enable the outcome to be predicted with certainty for any type of measurement process to which the system could conceivably be subjected. Solution of the core measurement problem, however, overcomes the conceptual intractability of non-ordinary objects. It enables quantum theory to accommodate and work comfortably with them in a logically comprehensible way that does not demand abandonment of "common sense".

2.2 Copenhagen

2.2.1 Copenhagen as a Physical Theory

Traditional quantum theory can be regarded as an artificially constrained subset of the realist framework, based on the combination of Q-1 (Rule 1) and Q-3 (Rule 2). It explicitly recognizes measurement processes only of a very specific form, which requires supposition of an overarching reality of dual structure - part quantum and part classical.

In a dualistic universe of this kind, quantum systems are isolated entities. From their perspectives, the rest of the universe behaves as a classical system. Rule 1 dynamics unfold unitarily and are self-contained in the quantum realm, but nothing interesting happens[5] until the classical surroundings intervene, triggering Rule 2. From the perspectives of both the quantum and the classical sides of the divide, the wavefunction is operationally meaningful only insofar as it serves as input to the Born Rule, which enables outcome probabilities to be computed.

[4]The term "interpretation", although widely considered unsatisfactory in quantum foundations, is used here simply for brevity.

[5]That is, there is no information transfer from the quantum system to the surroundings.

2.2.2 Centrality of Observers

Traditional quantum theory regards its own formal content (quantum mechanics) as meaningful only from the information- and control-theoretic standpoints of the classical surroundings. Those standpoints vis-à-vis a quantum system embody the concept of an *observer*.

An immediate consequence - indeed, tautology - is that quantum mechanics is inherently reliant on the existence of observers. Composite quantum systems can be assembled, interact and become entangled, and evolve unitarily under Rule 1, but traditional quantum theory relies on the supposition of a Heisenberg cut, *i.e.*, a space-time boundary that envelops the quantum system and separates it from classical surroundings. Only at that level does the theory confer meaning to the wavefunction. Such notions of cuts may be realistic and work well in laboratory settings, but they are clearly ill-suited to study of the cosmos, which, by definition, has no surroundings, classical or otherwise.

In this respect, the scope of traditional quantum theory is fundamentally self-limited. It not only falls short of encompassing the cosmos, but it also implicitly assumes the existence of physics laboratories and physicists.

2.2.3 Anti-Realism

The Copenhagen dispensation insists that the observer regard the quantum system as a sealed blackbox. It further stipulates that interaction with the blackbox (as long as it remains isolated as such) is through a simple two-way interface. First, the observer, acting as an *actuator*, subjects the quantum system to a certain type of measurement intervention[6]. The system responds by returning a measurement outcome (eigenvalue) and collapsing to a state in the associated eigenspace. That, in a nutshell, is experiment.

Copenhagen decrees that the formal content of the theory is limited to dialogue of that kind with Nature, and that all else is meaningless metaphysics. It permits development of cookbooks of mathematical models that describe regularities in the dialogue data, but it insistently maintains, as a matter of fundamental principle, that it is useless and misguided to attempt to explain the innards of the blackbox more deeply in terms of physics principles or intuition. In this respect, anti-realism is inherent in the structure of the theory itself.

As a general example of how anti-realism operates, consider how standard quantum theory reckons with non-deterministic phenomena. In practice, Q-2 is invoked under the guise of time-dependent perturbation theory. From an instrumentalist perspective, TDPT works in that it yields time-dependent probabilities that agree with experiment, but it is unsatisfactory from a realist perspective. The invocation of TDPT is an implicit acknowledgement that *something* non-deterministic occurs in the absence of observer intervention, but anti-realism bars the theory from being clear on the matter or offering any explanation. Anti-realism further denies that there is any matter to be curious about in the first place.

The instrumentalist rigor demanded by strict positivism is virtually impossible to uphold in practice, since much intuition inevitably does go into the crafting of phenomenological models (*e.g.,* Hamiltonians) that capture the data patterns. Moreover, phenomenological models derived from rigorously instrumentalist learning processes[7] of this kind, in their internal structure and information-theoretic complexity, are roughly commensurate with underlying physics in the realist theory.

2.2.4 Non-Classical Phenomenology

From the quantum phenomenology in the laboratory, there emerged in the first half of the 20th century a number of novel concepts that seemingly defied common sense intuition and were altogether foreign to experience in classical physics. They notably included: (*i*) non-determinism, (*ii*) non-locality, (*iii*) quantum jumps, (*iv*) wavefunction collapse, (*v*) spooky action at a distance, (*vi*) observer-created reality, and (*vii*) coexistence of Rule 1 and Rule 2 dynamics. Copenhagen exhorts us simply to accept them as the factual landscape of Nature in the microdomain and to disown old-fashioned classical reasoning that inhibits their acceptance. The difficulty of that was at the heart of the historic Bohr-Einstein debates, on which the realist framework concludes:

- Einstein was ultimately wrong about key aspects of the structure of physical reality, principally determinism and locality.

[6] Types of experimental measurement processes are formally expressed as Hermitean operators.

[7] In the context of statistical learning theory, this goes by the term *system identification*.

- Einstein was right in the EPR argumentation, which correctly identified need for a hidden variable (P-state) supplementing the wavefunction (W-state) for a complete description of quantum state.
- Einstein was right in his insistence that a realist understanding of Nature in the quantum realm is the *only truly satisfactory way of doing science.*
- Bohr was right that the strangeness of the quantum world is for real and must be accepted, no matter how jarring the implications.
- Bohr failed to offer any framework for making sense of the quantum phenomenology vis-à-vis the basic story-telling questions.
- Not only that, Bohr adamantly denied that there is any point in trying to make sense of it. As a consequence, Copenhagen hardened into an explicitly obscurantist ideology, which actively disparages and discourages all curiosity or effort to do so. In the long run, that has not served science well.

The realist framework accepts all of the aforementioned facets of non-classical phenomenology. It unequivocally embraces them as real features of Nature in the microdomain. It was shown in the preceding papers [15, 16] how they can be explained sensibly, once the core measurement problem is solved. From this new vantage point, standard quantum theory can be rehabilitated as a concise mathematical model of the phenomenology that carries minimal metaphysical baggage of its own, but that is supported by the deeper insight of the realist framework.

2.2.5 Wigner's Friend

In traditional quantum theory, the *only* role of the classical surroundings is to invoke the Born Rule on the quantum system of interest. The theory has nothing to say about the surroundings as a physical system in its own right. It takes a notably ambivalent and non-commital stance, which is exposed by the tale of Wigner's Friend.

The tale is concerned with a laboratory regarded as a composite system, the classical part of which is a physicist ("Wigner") studying the quantum part. The composite system is subject to observation by an outer observer - notionally Wigner's friend.

The traditional theory, in principle, permits two very different explanations of what happens. In one view, Wigner's act of observation produces a definitive and unambiguous single outcome. His friend's lack of knowledge before observing the laboratory is then a matter of classical ignorance. This can be regarded as the classical end of a spectrum of viable explanations[8].

That would be the clear consensus explanation, were the theory to place Wigner unequivocally on the classical side of a definitive Heisenberg cut within the laboratory, but traditional quantum theory is diffident and ambivalent on that. Conventional understanding leans toward the opposite end of the spectrum, which moves the cut to an outer level between the laboratory and the friend. In this view, Wigner, despite his macroscopic size, is considered a quantum system. The measurement event in the laboratory then produces not a single outcome, but a superposition of two wavefunction branches. One branch consists of spin-up for the small quantum system, in conjunction with Wigner perceiving a spin-up outcome; the other branch consists of spin-down in conjunction with Wigner perceiving a spin-down outcome. One outcome or the other becomes actual only when the friend peeks into the laboratory. This can be regarded as the quantum end of the spectrum of explanations in that the quantumness of the laboratory and the purity of the Q-1 dynamics driving it is maintained as long as possible.

If wavefunction collapse is deferred in this way, we are forced to take seriously the notion of macroscopic systems being in superpositions of different classical states. The two wavefunction branches ostensibly each occupy the same (3+1)-dimensional space-time that existed before the measurement event in the laboratory, but after that, they no longer interact and have nothing to do with one another. For all practical purposes, they constitute different *worlds*.

2.3 Many Worlds

In the 20th century, the Copenhagen dispensation was indisputably the orthodox consensus, which thoroughly shaped how quantum mechanics came to be understood, applied, and taught. In more recent times, however,

[8] The classical end of the spectrum is referred to further on as an "early decision" scenario.

Many Worlds has rivaled Copenhagen for dominance. Even that may be understatement; Many Worlds has arguably gained the upper hand, because it has found favor with many researchers working in fundamental physics (principally quantum gravity, cosmology, and elementary particle physics) and applied fields (*e.g.*, quantum computing, cryptography, and information science). It has many influential advocates and a strong following of adherents[9].

2.3.1 Ontic Stature of the Wavefunction

The Everettian view toward quantum theory eventually took root, albeit after a long period of indifference, because it correctly identified the need to ween traditional quantum theory from observers. Quite obviously, quantum theory cannot aspire to be a theory of principle encompassing the cosmos if its logical structure requires reference to observers inhabiting a classical realm outside the scope of quantum systems being investigated in laboratory settings. The only way out is to posit that the wavefunction must be ontic, as opposed to epistemic. That is, it is taken to represent an objectively real wave-like entity and state of Nature that exists in its own right, with or without observers.

The realist framework concurs with Many Worlds on the ontic stature of the wavefunction. However, the realist conception of W-state is significantly different from the wavefunction of conventional quantum theory, whose formalism Many Worlds accepts without modification. W-state has built-in thread structure, whereas conventional wavefunctions do not. In the Feynman formulation of quantum mechanics, the concept of threads translates to *alternative histories*, which can produce interference effects.

2.3.2 Removal of Heisenberg Cuts

Many Worlds is the reformation of traditional quantum theory that results from the explicit removal of cuts. There is then no longer any divide between distinctly classical and quantum subsystems, and Nature becomes all-quantum.

The lesson of Wigner's Friend is that if cuts are moved outward to envelop macroscopic subsystems, the concept of multiple worlds follows as a logical consequence and must therefore be entertained seriously. This is dramatically consequential. Because there is no wavefunction collapse, it follows that everything that can happen, quite literally, *does* happen. The apparent definiteness of measurement outcomes is held to be illusory because the wavefunctions of the small quantum system and observer both split and become mutually entangled. One apparent outcome occurs in one branch; different outcomes occur in other branches. Definiteness of measurement outcomes, wavefunction collapse, and quantum jumps are considered illusory because it applies only in here-and-now universes[10], which Many Worlds maintains are not the whole story of physical reality.

2.3.3 Determinism

Although Many Worlds is usually thought of as being a purely Rule 1 formulation of quantum mechanics, it does not really do away with Q-2 or Q-3. It implicitly holds that measurement events are objectively real and are governed by irreversible dynamics; otherwise, there would be no branching activity of which to speak. The bifurcation dynamics, despite their irreversibility, are strictly deterministic in that all possible measurement outcomes are retained and shunted into separate worlds.

Many Worlds treats Q-2 and Q-3 on what is much closer to an equal footing than Copenhagen. Both induce bifurcations, either via decoherence (Q-2) or contrived observer intervention (Q-3). Copenhagen, by contrast, treats the two very differently; it explicitly recognizes only Q-3, whereas Q-2 is recognized only implicitly in the guise of TDPT.

2.3.4 Non-Locality

Many Worlds proponents claim that Bell's theorem does not apply to their theory because of a loophole: the theorem assumes that local measurement processes select single definite outcomes. However, Bell inequality violations

[9] It can perhaps even be said that Many Worlds is the new quantum establishment.

[10] A "here-and-now" universe is a succession of branch segments, along which an observer, by his own reckoning, is carried.

are part of the phenomenology experienced in any here-and-now universe as much as definite measurement outcomes, wavefunction collapse, and quantum jumps. Many Worlds sidesteps their conceptual difficulty by denying that here-and-now universes are the whole story of physical reality.

2.3.5 Decoherence

The concept of *decoherence* is very general and not limited to Many Worlds. It signifies the physical causation of Q-2 dynamics. Decoherence arises, for the most part, from interactions between quantum systems and their surroundings. In Many Worlds, these precipitate bifurcations of the wavefunction into multiple branches.

The realist framework differs from Many Worlds in that it maintains that only one branch follows from any measurement event. The result is therefore a theory of a single world, rather than of many. Alternatively stated, the realist framework holds that there *is* only one here-and-now universe, and that that is the whole of physical reality.

Why was Everett averse to extinguishing the other worlds that we never see? As was noted in the tale of Wigner's Friend, this stance is not unique to Many Worlds, as Copenhagen is ambivalent about where to place cuts. There is a deep-seated tension [15] in the coexistence of Rule 1 and Rule 2, which has never been easily accepted. Everett regarded the coexistence of the two as ungainly and believed that the other worlds could not be extinguished without special rules or in any way that would make for a "clean" theory. He was not alone in that thinking, even in his day. Generally speaking, the prevailing sentiment has held that the two Rules cannot be intermeshed elegantly under a single theoretical roof. The result, both in Copenhagen and in Many Worlds, is a lopsided uncomfortable coexistence. Measurement processes are treated as exceptional in nature, and Q-1 reigns everywhere except where it does not.

The realist framework maintains that the solution of the core measurement problem enables Q-2 to be elevated to the stature of a full-fledged facet of quantum theory that does intermesh elegantly with Q-1. Unrealized measurement outcomes can then be extinguished without theoretical difficulty.

2.3.6 Many Worlds Complexity

Because Many Worlds offers no mechanism to extinguish branches, the result is a continually proliferating stupendous infinitude of branches diverging from one another and becoming separate worlds. In this respect, it fails badly on grounds of parsimony and complexity control. It implies that physics cannot fit into one world, and that there is no informationally compact way of representing wavefunctions[11] or how they change in any here-and-now universe.

2.4 Pilot Wave Theory

2.4.1 Particle Trajectories

Pilot wave theory, developed by Bohm and de Broglie, is noteworthy in that the particle trajectories that it envisages resemble the thread structure of W-state in the realist framework. Because Bohmian mechanics is parsimonious (*i.e.*, free of arbitrary parameters and unburdened by assumptions in its formalism), it is a straightforward and unambiguous matter to derive the trajectories.

In the realist framework, there are no particles as such in the W- or P-state ontology. However, thread trajectories, which are shaped by the Q-1 dynamics, mediate causal relationships within the W-state, which produce self-interference effects. If the trajectories in pilot wave theory were interpreted this way, it would eliminate the issue of the pilot waves pushing on the particles without reciprocity.

2.4.2 Deeper Explanation of the Born Rule

Pilot wave theory is also noteworthy because it offers explanation of the Born Rule based on deeper principles. Only ensembles of particle distributions consistent with the Born Rule are stable. In the realist framework, this corresponds to scenarios in which the system is in a default P-state (*e.g.*, as in EPR experiments before either piece is measured).

[11] More precisely, relevant facets of the wavefunction of the universe.

In standard quantum theory, sets of possible measurement outcomes are represented as mutually orthogonal eigenfunctions in a Hilbert space. The expression for the inner product of the pre-measurement W-state with itself is a sum of square-amplitude terms[12] for each outcome. Because the terms are all positive-valued and sum to unity, they have the requisite mathematical properties to be *interpreted* as probabilities. Pilot wave theory goes further to offer mechanistic explanation of *how* the probability values come about in Nature.

2.5 GRW

Physical collapse theories such as GRW are noteworthy in that they are the only well-known formulations of quantum theory that take Q-2 seriously, *i.e.*, recognize wavefunction collapse or narrowing as a real feature of Nature. As such, it draws attention to the place and status of Q-2 in the overall structure of quantum theory.

2.5.1 Wavefunction Collapse

The realist framework regards spontaneous indeterministic W-state dynamics as a real feature of Nature in the microdomain and integrates it into the tripartite structure. It is better considered "wavefunction narrowing" rather than collapse, as there is continual interplay between Q-1 and Q-2. The framework further maintains that well-known phenomena such as spontaneous emission and tunneling are forms of Q-2 dynamics, not fundamentally unlike GRW processes.

2.5.2 Intermediate Status of Q-2

What is the overall importance of Q-2 vis-à-vis Q-1? Consider first the one hypothetical extreme, in which Q-2 is altogether nonexistent. There would then be nothing but purely deterministic time-reversible wavefunction evolution. There would be no measurement events, no arrow of time, no Born Rule, no Everettian bifurcations, and no spontaneous quantum phenomenology. In short, there would be no interesting physics, and so we can immediately rule this out as a description of Nature. In the opposite extreme, Q-2 would dominate. There would then be no interference effects, and the non-zeroness of $\hbar$ would never become manifest.

The upshot is that Q-2 is necessarily of intermediate importance, somewhere between the extremes. There is no alternative other than to accept that, but it runs contrary to the long-standing quest for unification in physics, which relentlessly seeks parsimony and tends to favor all-or-nothing simplicity. Loosely speaking, values of zero (0) or infinity (∞) in a physical theory are considered ideally parsimonious and eliminate need for further explanation. Anything intermediate is regarded as an introduction of a new unexplained parameter, which increases the complexity of the theory. In practice, that is generally considered disadvantageous not only because it makes the formalism more ungainly, but also because it makes the theory more resistant to falsification.

On the other hand, Nature does not necessarily always cooperate with theorists' desire for supreme parsimony and elegance. The Standard Model is the premier case in point.

2.5.3 Free Particle Dynamics under GRW

GRW, as a formulation of quantum theory that incorporates Q-2 in a direct and explicit way, is interesting in that it offers a non-standard account of what Nature may be doing when nobody is looking. Consider the most basic abstraction of a quantum system: a free particle. Standard quantum theory tells a story of an expanding wavepacket, which is awkward and questionable in certain respects [15]. GRW offers an alternative story of a wavepacket that maintains more or less constant width, but whose center executes random walk motion[13].

In the realist framework, both stories are regarded as plausible theories of quantum dynamics in the absence of observer intervention. One is closer to the truth of Nature than the other, but the framework does not rule out either on *a priori* grounds. Both fully answer the basic questions as required by any realist theory, but they differ on the question of whether measurement events occur early or late (or, equivalently, where Nature places the cut). The wavepacket expansion of standard quantum theory is said to be the *late decision* scenario in that the measurement outcome is not decided until the latest point possible (*i.e.*, when an observer looks). The random walk is the *early decision* scenario in that spontaneous wavefunction narrowing is continually intervening. As a

[12] Because the eigenfunctions are othogonal, cross-terms in the inner product vanish.

[13] Despite the movement of the center, conservation of momentum is technically not violated, even over long periods.

physical theory, it is more complex than the wavepacket expansion in that it requires introduction of at least one free parameter (*e.g.*, the ratio of the steady-state packet width to the Compton wavelength).

The early vs. late decision ambivalence is equivalent to the question of the scale at which Nature places the transition between the quantum and classical realms. We know informally that the scale has to be somewhere between zero and infinity. The late decision scenario, in effect, places the divide at infinity. That results in a more parsimonious and theoretically elegant theory in that it banishes measurement dynamics until an observer intervenes. That may, in some cases, be a correct theory of how Nature actually operates, but only for microscopic systems. It definitely does not apply in single-world theories to macroscopic systems, as that leads to the absurdity of the Schrödinger cat.

2.5.4 Spontaneous Emission

Consider the simple problem of spontaneous emission. An excited atomic electron radiatively drops to the ground state, emitting a photon. A question comes up: Is the direction of photon emission, and reciprocally the recoil of the atom, established at the time of emission, or does it remain undecided until the photon is intercepted by a detection device?

The realist framework can accommodate wide latitude in the possible answers. One is a late decision scenario, in which the photon directionality is completely indeterminate after the emission. The post-emission W-state of the photon and atom would both be spherically symmetric. When the photon is detected, the P-state of the atom would instantaneously change, such that its direction of recoil momentum is found to be opposite that of the photon when it is eventually measured. Conversely, if the atom decoheres first by bumping into something, the directionality of the photon, still in flight, would become constrained[14].

A different answer is the early decision scenario, in which the directionality is determined at the time of emission. The W-state of the photon would be a pencil beam, rather than a spherical shell. Atomic physics insight may weigh in on whether the early or late decision scenario is more correct, but that is separate from the ability of the framework to accommodate a spectrum of scenarios.

Realism, being more curious than instrumentalism, asks questions like this about what happens in the microdomain. It invites us to *think about* Nature in more detail at this kind of deeper level, but it does not necessarily demand that our theories become commensurately more complex or take a stance. It offers a spectrum of pictures about how Nature might operate, but it also recognizes that it may be beyond the reach of *science*[15] to offer conclusive answers.

2.6 QBism

QBism, which treats the wavefunction as epistemic, would seem to have the least in common with the realist framework. Perhaps surprisingly, however, that is not so. P-state can be interpreted and treated mathematically in terms of Bayesian probability theory and belief networks. This is noteworthy in that it is a physical realization of Bayesian probability in Nature, in the absence of observers and therefore having nothing to do with *belief* in the usual sense.

3 Realist View Toward Quantum Electrodynamics

It is thoroughly well-known and appreciated that quantum electrodynamics (QED) is widely regarded as the single most spectacularly successful theory in all of science. The fantastically precise agreement with experiment that it has reported is legendary and an unforgotten success story.

That being acknowledged, the realist framework does not shy from the contention that QED needs to be rebuilt from the ground up. Ostensible success should not be a deterrent to seeking to understand QED more deeply, vis-à-vis questions of what, where, when, and how. It is often said that Feynman diagrams should not be interpreted too literally, but that cannot be the last word from a realist perspective. The need for renormalization recipes, no

[14] Its W-state would remain spherically symmetric. The P-state constraint takes effect when the photon is detected.
[15] Science, meaning either as a philosophical matter or in human terms of actual practice.

matter how impressive the agreement with experiment, only exposes and underscores the limitations of instrumentalism and lack of adequate understanding of how Nature really produces finite quantitative answers. Furthermore, there are more basic aspects of the interaction between matter and radiation that are seldom discussed.

3.1 Photons

What really are photons? That is a question that any realist view toward quantum theory must aspire to answer. It has been known since the time of Planck and Einstein that radiant energy comes in quantized lumps, and since the Compton experiments that those lumps carry momentum. That much has long been established common knowledge, but it immediately poses several questions.

3.1.1 Intermeshing of Classical and Quantum Theories

The first question is how that corpuscular conception of light can mesh with the smooth and continuous character of classical electromagnetic theory. This is not very different from the problem of squaring with quantum theory with general relativity. The fabrics of reality envisaged by classical physics and quantum physics are night-and-day different. What is amazing, in retrospect, is that physics has done so well over the last 120 years, despite not really knowing how to intermesh the two.

3.1.2 Generality of Classical Electromagnetism

Photons embody radiant energy, which arises in only special subsets of solutions of Maxwell's equations. Planck's photons, in textbook derivations of the blackbody spectrum, are standing wave solutions in an enclosed cavity. Out in the open, such as in the photoelectric effect or Compton scattering, they correspond to propagating wave solutions.

Classical electromagnetism is marvelously impressive because of its extremely broad generality and versatility. It encompasses and seamlessly unifies electrostatics, radiant energy in standing and propagating forms, and all variety of forms in between under a single theoretical roof with a small handful of equations. Photons do not span that broad gamut of generality and therefore do not represent electromagnetic fields comprehensively. How, for example, are electrostatic fields described in terms of photons? The short answer is that they are not described in terms of photons. In atomic physics, the electrostatic field of the nucleus is incorporated into the Schrödinger equation simply as a classical Coulomb potential.

3.1.3 Sourcing of Electromagnetic Fields

Photons are remiss in a third respect. In classical electromagnetism, fields are associated with sources, directly (*e.g.*, as in electrostatics) or indirectly (*e.g.*, propagating radiation). In quantum theory, however, no such association is evident; photons are simply created or destroyed.

3.2 Source Particles and Electrostatic Fields

We begin with matter particles, the realist quantum theory of which was developed in the two preceding papers [15, 16], and investigate how they can be modeled as sources of electrostatic fields. The W-state of the particles consists of short threads[16], which are classical elements of reality having sharply defined position and momentum. It seems reasonable to postulate that these act as field sources, exactly as in classical electromagnetism.

3.2.1 Combination of Classical and Quantum Superposition

In a quantum superposition, two or more different classical situations coexist. It stands to reason that different source situations result in different field situations, *i.e.*, a quantum superposition of fields. However, that cannot be the entire story, because there is the complication that there are two types of superposition at work - one quantum and one classical.

As was noted earlier, there are two forms of quantum superposition: local and distributed. In local superposition, a particle intersects itself, going at multiple different velocities. Nothing akin to that exists in classical field

[16] *Short thread* is a term of differential geometry, signifying a local piece of a long thread (world line).

theory; the source matter at any point in space-time is represented completely by a charge-current density vector, $(\underline{J}, c\rho)$. In distributed superposition, W-state is spatially spread out, as required by the uncertainty principle. That is interpreted as coexistence of mutually incompatible classical situations, which is profoundly different from continuous distributions of matter in classical theory.

In classical electromagnetism, fields arise from distributed sources. Field contributions from the charge-current density at the various source points sum vectorially to produce a single field tensor value at any point. A single classical situation at any point exists for the fields, just as for the sources.

If electromagnetic fields sourced by charged quantum particles were derived entirely from classical superposition, the thread structure of the source W-state would not be completely reflected in the fields, as local superpositions would be ignored. The fields must therefore somehow be derived from a combination of classical and quantum superposition.

3.2.2 Partitioned Thread Structure of Charged Particles

A proposed solution is to think of charged particles as having a partitioned thread structure. Any two short threads in the same equivalence class are such that their contributions to the field at any point combine vectorially (*i.e.*, classical superposition). An equivalence class of short threads thus gives rise to a classical electromagnetic field - thus, a single classical situation at any point in the field space. For different equivalence classes, the resulting classical fields combine via quantum superposition. The overall result is therefore a superposition of classical fields - that is, a quantum field. The quantum field is spread out in space around the W-state of the source particles.

How can we say what the equivalence classes look like? Consider the set of short threads on a shared rest manifold[17] of the source particles. These contribute to the field at all space-time points causally downstream of the manifold, via the Maxwell equations. Short threads on the manifold whose velocity vectors are aligned form the equivalence classes.

3.2.3 What is Charge?

A pure quantum wave [15] is the simplest abstraction of elemental quantum reality. In its rest frame, it is characterized by a constant phase rate[18], which has one sign (*e.g.*, "positive") for positively charged particles and opposite sign for negatively charged particles. In this conception, quantum waves reify the idea that particles and anti-particles travel in opposite time directions.

In the realist framework, electric charge is regarded as an inherent attribute of threads composing the W-state of charged particles. Electric charge is a distinctive and unique attribute in that it sources long-range fields that are signed. The same is true of gravitational mass, except that it sources long-range fields that are not signed.

In this view of thread attributes, that is the last word on Einstein's quest to unify gravity and electromagnetism. The two are unified in that they are shown to be fundamentally *different*. Much, however, remains to be explained, including their vastly different strengths and why one but not the other is nonlinear.

Neutrino threads are different from lepton[19] and quark threads in that they lack the electric charge attribute. However, they come in pairs, wherein neutrino and anti-neutrino threads are distinguished by their opposite phase rates. Particle-antiparticle pairing, and possibly also partitioned thread structure, is common to quarks, leptons, and neutrinos and may therefore have something to do with weak interactions and transformation processes.

Quark threads are different from leptons and neutrinos in that they have two charge attributes: electric and color. As such, quarks are the only elementary fermions that can participate in strong nuclear interactions. Additional thread attributes distinguish amongst the three families in the Standard Model and the two quarks within each family.

3.3 Radiative Fields

What has been developed thus far is a quantum theory of electrostatic (and magnetostatic) fields. This is valid for the nuclear Coulomb field felt by atomic electrons and the fields sourced by electrons in the ground state, but we know that it cannot be completely general because it does not account for photons.

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[17] Systems of entangled particles have a shared rest manifold.

[18] Phase rate is determined by a Lagrangian function driving the Q-1 dynamics.

[19] *Lepton*, as used herein, specifically excludes neutrinos.

3.3.1 Weakly Perturbed Static Fields

We consider first the case in which the W-state of the source particles is stable, but hypothetically shaken gently. How is the field affected?

In classical electromagnetism, any acceleration by the source, no matter how small, induces disturbance in the field, which translates to radiant energy emission. In the quantum realm, the non-zeroness of $\hbar$ precludes that. It follows that the field does not radiate unless the perturbed source motion exceeds some critical threshold. Below that, the field merely shakes quasi-statically in tandem with the source distribution.

3.3.2 Radiative Drops from Excited States

We next consider excited atomic electrons. They remain excited for a very short time, before emitting a photon and dropping back to the ground state. But how does the electron "know" that it is excited? How does it know about the availability of the ground state? What nudges it to undergo the transition? How is the photon formed?

In textbook quantum mechanics, QED, together with TDPT, yields a formulaic expression for a transition rate, but a more visualizable understanding is now sought. We are interested in where, when, and how.

It is first noted that that the emission process is not purely deterministic, because the transition time is not pre-determined. It is governed by a probability distribution. It follows that Q-2 and Q-1 dynamics must both be at work. Insofar as both dynamics are non-local, the electron is able to become "aware" of its global configuration, which features an energy gradient down toward the vacant ground state. It begins to drop, but it somehow needs to shed off the extra energy and determine how much to shed.

At first, the electron does not know precisely the magnitude of the drop, as it has not yet been able to feel out the ground state. The formation of the photon does not take final shape until the drop is complete, as the exact amount of energy is not definitely established until then.

3.3.3 Light Quanta

There are static electromagnetic fields, and then there are photons. How can we visualize the coexistence of the two?

Think of source charges as little rocks, and the electrostatic field as a watery film that completely envelops the rock and is inseparable from it. The rock cannot be touched without getting one's hand wet. Shake the rock gently, and the surrounding water moves quasi-statically in tandem with it. If two rocks are brought close together, their water fields will partially coalesce. Pull the rocks apart, and their fields dissociate and return to their exact previous volumes and shapes.

Now what happens if we impart more energy by shaking the rock more vigorously? How does the energy get radiated away? Quantum theory tells us that radiant energy is always quantized. In our fictional setting, that means that little water droplets of standard size and energy content (proportional to the frequency of our shaking) bud off from the enveloping film and fly away. A droplet remains in flight until it encounters the water field of another rock. The droplet seamlessly coalesces with the water field enveloping that rock, and all of its energy is converted into kinetic energy of the rock.

This fictional tale offers a realist kind of explanation to the three questions about photons that were posed above. First, it paints a picture of how corpuscularity and smooth continuity can coexist harmoniously. Second, it shows how photons can exist as a subset of the wide variety of field solutions of Maxwell's equations. It posits a sharp qualitative dichotomy of fundamental nature between static and radiative fields. Third, it retains the association between sources and fields that classical electromagnetism upholds.

It is a truly remarkable feature of Nature that electromagnetism in the quantum realm is like. Its most distinctively non-classical feature is radiant energy quantization. If photons seem unremarkable, it is only because they were the first manifestation of the quantum world that came to our attention 120 years ago.

3.4 Realist Explanation of the Aharonov-Bohm Effect

We lastly discuss how the Aharonov-Bohm (AB) Effect can be understood in realist terms. It is the two-slit experiment with a solenoid placed midway between the slits. As electrons are shot through the apparatus, their W-state divides and works its way through the slits, steering clear of the coil.

When the two halves of the W-state recombine, it is found that the interference pattern on the screen shifts, by an amount dependent on the solenoid current. This is a puzzling phenomenon because it cannot be explained by classical electromagnetic theory. Because the electromagnetic fields ($\boldsymbol{E}$ and $\boldsymbol{B}$) outside the solenoid are zero, the presence of the solenoid should have no effect on the electron motion through the apparatus or the interference pattern.

Standard quantum theory readily explains the phenomenon by showing that the shift is proportional to the vector potential, $\boldsymbol{A}$, integrated over a closed loop circumscribing the solenoid. As an instrumentalist explanation, this clearly works and is correct, but it offers no insight into how the W-state is able to sample the information content of the line integral, considering that the $\boldsymbol{A}$ field itself has no local meaning of its own.

The dynamics in the two-slit experiment are purely Q-1 deterministic, but the AB effect clearly shows that the dynamics must be non-local. The W-state itself bypasses the solenoid, but its rest manifolds do not. They are spread out and fully intercept the entire apparatus. The rest manifold is well-defined and exists even where the W-state amplitude is negligibly small. As the two halves of the W-state pass through the slits, their rest manifold cuts through the solenoid and samples the current. Non-local Q-1 dynamics then affect phase rates in the W-state halves in a gauge-invariant way.

A final word about the two-slit experiment. Feynman further said that the full extent of quantum mystery is encapsulated in the experiment, but that is not true. Identical particle interchange is at the heart of quantum foundations and defies classical intuition as much as any facet of quantum phenomenology, but it is irrelevant in the two-slit experiment because only one electron at a time transits through the apparatus. Electron spin is also irrelevant in the experiment.

4 Perspectives on Quantum Gravity

4.1 Importance of the Quantum Gravity Problem

Should we give up on quantum gravity? Is it worthwhile continuing to try to solve it? One view says no, principally because the two theories have no common physical ground. The scale gap between the domains in which general relativity and quantum theory hold sway is so vast that the two really do have nothing to do with one another. Any theory of quantum gravity is therefore untestable and beyond the scope of science proper.

A different view holds that even if there is no common physical ground, quantum gravity is a uniquely important problem in its own right because it is about the two most important theories of principle in physics. Testable predictions and new phenomenology are ultimately beside the point. The quantum gravity problem is better regarded as stress tests for the two theories separately[20].

In order for both theories to be considered robustly and versatilely formulated, they must be shown to intermesh elegantly. General relativity, as a classical theory that has withstood all experimental scrutiny, is already at that level. Quantum theory is not, as long as it is plagued by foundational issues. A realist framework is absolutely necessary to overcome that and bring quantum theory to a level at which an intermeshing with general relativity stands to succeed.

4.2 Scope and Ambition of the Quantum Gravity Problem

Most quantum gravity research has been premised on the assumptions that (i) common physical ground exists, and that (ii) it is important to find and make a business case for investigating it, however exotic it may be. That has led to focus on the Planck regime, which is so extreme that the structure of space-time, as we conventionally know it, breaks down. That has made the research programs, such as loop quantum gravity (LQG), maximally ambitious – and arguably too difficult. Perhaps a better way to approach quantum gravity is a graduated one, based on a spectrum of general relativity regimes:

- **Level 1**: This is the regime of very weak gravity, which does not distort the flat Euclidean backdrop of special relativity appreciably. Newtonian gravity may be freshman physics, but its non-zeroness is enough to produce noticeable time dilatation effects that figure importantly in terrestrial experiments (*e.g.*, Pound-Rebka) and GPS technology. The most basic test for any quantum gravity solution is to show how quantum

[20]Not unlike how computing digits of pi is a stress test for high-performance computational hardware.

theory, at one elevation in a gravitational potential, morphs smoothly and continuously to another level, at which clocks run at a different rate.

- **Level 2**: This is the regime in which the linear approximation of general relativity applies. It encompasses most of the interesting manifestations of general relativity within the solar system. It is the next most basic test for quantum gravity, which must account for how quantum theory naturally adapts to a mildly non-Euclidean spatial backdrop.

- **Level 3**: This is the regime in which nonlinear corrections become appreciable. It is significantly more challenging for quantum gravity in two respects. First, the nonlinear backdrop precludes quantizing gravity in the old traditional way, which has been tried unsuccessfully many times. Second, the problem of gravitizing quantum theory is more complicated than in the linear regime. Its solution must be able to explain how gravitational fields depend nonlinearly on energy-momentum distributions, which are ultimately of quantum nature. The solution must also expose and underscore the similarity of – as well as essential differences in – gravitational and electromagnetic fields in a realist quantum-theoretic framework (*e.g.*, radiative energy quantization in gravitons).

- **Level 4**: This is the regime of ultra-strong gravity, as it exists in the observable universe and is accessible to observation. This means principally black holes, where general relativity is stretched to its limits as a classical theory. Most of the work in quantum cosmology since the time of Wheeler lies in this regime. Quantum effects figure importantly because they act as a bulwark against total collapse to singularity. A quantum gravity solution at this level would, at minimum, account for all phenomenology that well-established physical theory (*i.e.*, general relativity and the Standard Model) explains. It *may* go further to propose solution ideas for the harder unsolved problems of dark matter and dark energy, but that is not an essential criterion of success[21].

- **Level 5**: This is the Planck regime, in which the smooth continuous classical structure of space-time breaks down and presumably must be replaced by something radically different. It is beyond the reach of observational astronomy and is thought to apply only to the very early universe right after the Big Bang.

LQG and the other research approaches have focused almost exclusively on Level 5. The lower levels are implicitly regarded as uninteresting and unimportant, but that seems absurd. The intermediate levels represent a set of basic problems that quantum gravity must first address and solve before the most radical departure from the status quo (*i.e.*, the shredding of space-time itself) can be entertained and undertaken. The intermediate levels are centrally important in the aforementioned need to stress-test quantum theory. An intermeshing of quantum theory and general relativity would reveal how well the assumption of smooth and continuous space-time holds up across the levels.

[21] We would only be able to say that in retrospect, after dark matter or dark energy is solved.

References

[1] J. Barrow. *The Constants of Nature - From Alpha to Omega*. 2002.

[2] A. Becker. *What is Real? The Unfinished Quest for the Meaning of Quantum Physics*. 2018.

[3] M. Ben-Ari. *Just a Theory: Exploring the Nature of Science*. 2005.

[4] S. Carroll. *Something Deeply Hidden: Quantum Worlds and the Emergence of Spacetime*. 2019.

[5] O. Consa. "Something is Wrong in the State of QED". In: *ArXiv e-prints* (2021). arXiv: `2110.02078`.

[6] P. Davies. *Cosmic Jackpot: Why Our Universe is Just Right for Life*. 2007.

[7] P. Davies. *Other Worlds: A Portrait of Nature in Rebellion*. 1980.

[8] O. Freire. *The Quantum Dissidents: Rebuilding the Foundations of Quantum Mechanics (1950-1990)*. 2015.

[9] M. Gell-Mann. *The Quark and the Jaguar*. 1994.

[10] J. Gribbin. *Schrödinger's Kittens and the Search for Reality Solving the Quantum Mysteries*. 1995.

[11] N. Herbert. *Quantum Reality: Beyond the New Physics*. 1987.

[12] P. Holland. *The Quantum Theory of Motion: An Account of the de Broglie-Bohm Causal Interpretation of Quantum Mechanics*. 1995.

[13] R.I.G. Hughes. *The Structure and Interpretation of Quantum Mechanics*. 1992.

[14] M. Kumar. *Quantum: Einstein, Bohr, and the Great Debate about the Nature of Reality*. 2008.

[15] E. Larson. "A New Foundation for Standard Quantum Theory". In: *viXra e-prints* (2024). viXra: `2402.0149`.

[16] E. Larson. "A New Foundation for Standard Quantum Theory: Refinement and Prelude to Quantum Gravity". In: *viXra e-prints* (2024). viXra: `2406.0113`.

[17] D. Lindley. *The End of Physics: The Myth of a Unified Theory*. 1993.

[18] D. Lindley. *Uncertainty: Einstein, Heisenberg, Bohr, and the Struggle for the Soul of Science*. 2007.

[19] S. Lloyd. *Programming the Universe: A Quantum Computer Scientist Takes on the Cosmos*. 2006.

[20] W.E. Maudlin. *Philosophy of Physics: Quantum Theory*. 2019.

[21] G. Musser. *Spooky Action at at Distance*. 2015.

[22] R. Nadeau and M. Kafatos. *The Non-Local Universe: The New Physics and Matters of the Mind*. 1999.

[23] H. Ohanian. *Gravitation and Spacetime*. 1976.

[24] C. Rovelli. *Helgoland: Making Sense of the Quantum Revolution*. 2020.

[25] R. Shankar. *Principles of Quantum Mechanics*. 1994.

[26] L. Smolin. *Einstein's Unfinished Revolution: The Search for What Lies Beyond the Quantum*. 2019.

[27] L. Smolin. *The Trouble with Physics: The Rise of String Theory, The Fall of a Science, and What Comes Next*. 2007.

[28] L. Susskind and G. Hrabovsky. *The Theoretical Minimum: What You Need to Know to Start Doing Physics*. 2013.

[29] S. Treiman. *The Odd Quantum*. 1999.

[30] A. Wallace. *Choosing Reality: A Contemplative View of Physics and the Mind*. 1989.

[31] F. Wilczek. *A Beautiful Question: Finding Nature's Deepest Design*. 2015.

[32] F. Wilczek. *Fundamentals: Ten Keys to Reality*. 2021.