

## Article

# The Magical “Born Rule” and Quantum “Measurement”: Implications for Physics

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**Abstract:** I. The arena of quantum mechanics and quantum field theory is the abstract, unobserved and unobservable,  $M$ -dimensional formal Hilbert space  $\neq$  spacetime. II. The arena of observations—and, more generally, of *all* events (i.e., *everything*) in the real physical world—is the classical four-dimensional physical spacetime. III. The “Born rule” is the random process “magically” transforming I into II. Wavefunctions are superposed and entangled only in the abstract space I, *never* in spacetime II. Attempted formulations of quantum theory directly in real physical spacetime actually constitute examples of “locally real” theories, as defined by Clauser and Horne, and are therefore *already empirically refuted* by the numerous tests of Bell’s theorem in real, controlled experiments in laboratories here on Earth. *Observed* quantum entities (i.e., events) are *never* superposed or entangled as they: (1) exclusively “live” (manifest) in real physical spacetime and (2) are not described by entangled wavefunctions after “measurement” effectuated by III. When separated and treated correctly in this way, a number of fundamental problems and “paradoxes” of quantum theory vs. relativity (i.e., spacetime) simply vanish, such as the black hole information paradox, the infinite zero-point energy of quantum field theory and the quantization of general relativity.

**Keywords:** Born rule; quantum measurement; quantum to classical



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## 1. Introduction: Quantum to Classical

I. Quantum theory lives in abstract Hilbert space  $H^M$ , which, more often than not, is infinite-dimensional  $H^\infty$  [1]. Complex quantum wavefunctions,  $\psi$  (= vectors in  $H^M$ ), for  $N$  discrete quantum entities are defined in *configuration* space of  $3N$  dimensions (if their spins are zero),  $\psi = \psi(q_1, \dots, q_{3N})$ . The quantum state (i.e., the value of  $\psi$ ) is determined by simultaneously giving all numerical values of the  $3N$  variables ( $q_1, \dots, q_{3N}$ ). The time-dependence of  $\psi$  is only implicit, as  $t$  is neither an operator nor a variable in configuration space but merely a parameter, where  $\psi_t = \exp^{-it\hat{H}/\hbar} \psi_0$ , and this “dynamics” occurs in abstract, complex Hilbert space, *not* in spacetime. Also, being a global phase factor,  $t$  is unobservable. There is no spacetime description of  $\psi$ , so relativistic causality is not definable. The quantum states are normalized,  $\int |\psi(q_1, \dots, q_{3N})|^2 dq_1 \dots dq_{3N} = 1$  (i.e.,  $\psi$  lies at a point on the surface of the unit sphere in Hilbert space).

II. Classical physics lives in four-dimensional physical spacetime: the Lorentzian manifold  $L^4$ .

III. Upon “measurement”, the “Born rule” [2] is *postulated* to irreversibly, instantaneously, and randomly map  $H^M$  into specific points (= *events*; i.e., particular outcomes) in  $L^4$  with calculable probabilities. The joint probability density of *finding*  $N$  “particles” in  $N$  *detectors* in *real* space at time  $t$  (i.e., in  $L^4$ ) upon “measurement” is calculated by  $|\psi(\bar{r}_1, \dots, \bar{r}_N)|^2$ . Observe that there is *no* real spatial dependence for  $\psi$  until this “measurement”. The “fundamental” statistical character of “quantum theory” is actually only introduced here in III due to the “Born rule”. Everything we ever measure (e.g., using laboratory “detectors”), perceive, or experience occurs in *spacetime*, but it is only the eigenvalues that can be observed in  $L^4$ , and the quantum eigenfunctions still reside in  $H^M$  (they constitute bases there), even after application of the “Born rule”. The “Born rule” is “magical” in the

sense that there are no physical dynamics underlying it *and* in the sense that it transforms *unobservable*  $H^M$  into *observable* events in  $L^4$ . Upon “measurement”, the wavefunction  $\psi$ , with complex quantum amplitudes  $c_n = \langle n|\psi \rangle$  in eigenbase  $|n\rangle$ , randomly “collapses” (“jumps”) to *one* of the eigenfunctions  $|n\rangle$  of the—for observables—allowed Hermitian operators  $\hat{O}_n$  (assuring real eigenvalues  $o_n$ )

$$\hat{O}_n \psi = \hat{O}_n \sum_n |n\rangle \langle n|\psi \rangle \xrightarrow{\text{“meas”}} o_k c_k |k\rangle. \quad (1)$$

Each individual “jump”,  $\psi \rightarrow |k\rangle$ , resulting in the observed eigenvalue,  $o_k$ , is *a priori* postulated to occur randomly but with statistical probability (over *many* identical measurements) given by  $|c_k|^2 = |\langle k|\psi \rangle|^2$ . It is not the operators themselves that are observed; they only operate in Hilbert space, *not* in spacetime. It is the eigenvalues that are observed, and then only indirectly as a result of “measurement” (Equation (1)), transforming I into real events in II as a result of III.

However, we only infer I and III *indirectly* through observations, experiments, and experiences in II—the only world we have direct access to. *Observed* observables (= events) live in  $L^4$ . Quantum entities solely live in  $H^M$  and *have no classical properties*. The “measurement” transforms the infinitely many abstract quantum potentialities in  $H^M$  into perfectly mundane actual occurrences in  $L^4$ . Consequently, this shows that “decoherence” [3] *cannot* be a solution to the “measurement problem” [4–8] in quantum mechanics because: (i) it does not realize *any* objective outcome (unlike the “Born rule”) and (ii) if it did, it would mean that our classical world would be *manifestly non-local* (as decoherence is based purely on the wholly deterministic non-local “dynamics” of I). In pure quantum theory (without the “Born rule”), there cannot be any mixed states, as *probability presumes* prior measurement.

Hence, we see that statistically correlated *observed* “quantum” non-locality in spacetime in practice actually *only* arises through the magical “Born rule”. However, it still poses serious problems, as the *results* of measurement (*after* the “Born rule”) are *objective classical* events in  $L^4$  (e.g., data printouts on paper), *but* “simultaneous” is *not* relativistically invariant: in a canonical entangled-pair experiment, with correlated observables A and B at either end, for an observer moving relative to the lab (with any non-zero velocity  $v$ , however small,  $|v| = \epsilon > 0$ ), A is prior to B if  $v > 0$  (A is the “cause” of B and the “Born collapse” is *not* instantaneous), but B is prior to A if  $v < 0$  (B is the “cause” of A and the “Born collapse” is *not* instantaneous), if A is simultaneous with B in the lab-frame ( $v = 0$ ) [9]. The problem is that the “Born rule” is formulated in an *absolute* frame, the one where  $v = 0$ .

“Reality” occurs *only* in the spacetime of events—where the actual events are the fundamental, relativistically invariant, and irreducible building blocks of objective reality [10]. It is only here, in II, that all experimental results, and everything else we ever perceive, actually occur. That is why Bohr was fond of saying: “There is no quantum world” [11], only an abstract quantum *algorithm*, I together with III, allowing us to relate experiences in the real world II—the only one. There is no “quantum” reality, there are no “quantum” events, only a *classical reality* and *classical events*. Every time a “quantum” probability is calculated, it is really a result of “Born” III, *not* of pure (unmeasured) quantum theory I. Likewise, there are no “quantum” particle reactions in *spacetime*, only observed consequences in  $L^4$ . So, only II is really real, I and III merely abstract and unobservable machinery, very much like a black box we cannot peer into but with observable inputs and outputs. In a very real sense, the “quantum world” is operationally built up of events in our real world, not the other way around. Reality does *not* occur in Hilbert space  $H^M$ . This also means that there are no fundamental quantum entities in *spacetime*, only in (unobservable) Hilbert space.

The *interaction* in quantum theory I is *non-local* in non-relativistic quantum mechanics (e.g., Schrödinger’s) and *local* in relativistic quantum theory (Dirac/quantum field theory), but the wavefunction is *non-local* in *both* (but only implicitly in abstract Hilbert space, not in spacetime).

Wavefunctions are entangled [12] only in Hilbert space, *not* in real physical spacetime.

The dynamical real spacetime itself (II) is local. The entanglement superposition (in  $H^M$ ) is broken by the measurement,  $I \xrightarrow{\text{III}} \text{II}$ ; hence, there is *never* any non-causal *entanglement* in real spacetime  $L^4$ . Only classical particles and fields are defined directly in  $L^4$ .

III is *non-local* [13] in real *spacetime*. It correlates space-like separated events in our *real world*. However, particles “manifest” as events only as a result of “measurement” (through the “Born rule”)—it is therefore fundamentally *wrong* to assume that they separate and travel, moving apart in real physical space, to the detectors from the source while unobserved (in Hilbert space, they *neither* separate *nor* are “far apart”, as they are described by the *global* wavefunction in  $H^M$ ). The Bohm version [14] of the EPR-gedankenexperiment [13] *disregards* the actual “measurement”, as the *spatial* part ( $\psi_{\text{space}}$ ) of the *total* wavefunction is omitted/implicit. As we know today, it *cannot* be factored,  $\psi_{\text{tot}} = \psi_{\text{tot}}(\bar{q}_1, \bar{q}_2, \bar{s}) \neq \psi_{\text{space}}\psi_{\text{spin}}$ , as  $\psi_{\text{tot}}$  is *global* and depends on both quantum entities in an entangled, *not* factorizable, way,  $\psi_{\text{space}} = \psi_{\text{space}}(\bar{q}_1, \bar{q}_2)$ ,  $\psi_{\text{spin}} = (|\uparrow\rangle_{\bar{q}_1}|\downarrow\rangle_{\bar{q}_2} - |\downarrow\rangle_{\bar{q}_1}|\uparrow\rangle_{\bar{q}_2})/\sqrt{2}$ . Only quantum entities that do *not* interact *and have never* interacted may be factorized. The “measurement” (“Born rule”) collapses *both* space- [13] and spin-parts [14] of  $\psi_{\text{tot}}$  (which, due to the spin-1/2 degree of freedom in this case, lives in  $H^{12}$ ) *at once*.

Unobserved quantum entities are always (merely abstract) “waves” in  $H^M$ , and observed quantum entities are always “particles” manifested as events in  $L^4$ —there is *never* any “particle–wave duality” in either space. Specifically, there is never any causal “quantum-wave” propagation in spacetime. This means that classical physics, II, can *never* be the limit  $\hbar \rightarrow 0$  of “pure” quantum theory, I.

The quantum description of a system of  $N$  entities (for  $N > 1$ ) cannot be embedded in real spacetime [15]—actually, the very formulation of quantum mechanics *precludes* its embedding in spacetime for  $N > 1$ . For example, the quark and gluon fields ( $M = \infty$ ) interacting “in” a proton never objectively exist as particles in spacetime—only when a “measurement” is made; for example, using deep inelastic scattering, the results of an “electron–quark collision”, mediated by a photon- or  $Z^0$ -field (*not* particle) in Hilbert space ( $H^\infty$ ) through the “Born rule”, become translated into some experimental signal in real 4D spacetime ( $L^4$ ).

Abstract configuration space  $(q_1, \dots, q_{3N})$  and physical space  $(x, y, z)$  can coincide *only* if there is only *one* (spinless) quantum entity, actually *measured* at  $(x, y, z)$ , in the entire universe (this, unfortunately, *precludes* any interactions, experiments, or observers); otherwise, they are distinct—and actually the origin of most confusion.

The “Born rule”, III, is just a random sampling, upon “measurement”, of the abstract, globally ever present, and completely *deterministic* Hilbert space—meaning that the (unobservable) “quantum world” is completely deterministic—determined by all the *unobserved* variables in configuration space, while the real world is local and uncertain in part due to our ignorance of the global/non-local “hidden variables” of configuration space.

We thus see that even *orthodox* quantum mechanics already, in a sense, *has* “hidden variables” in fact always present in configuration space, which globally keep track both of what has happened and also of everything that can ever happen—potentially including even the “decisions” of observers.

Even for two *free* quantum entities that have *ever* interacted in the past, measurement with one affects measurement with the other. For example, in energy eigenbase

$$\psi = A\psi_a(\bar{q}_1)\psi_b(\bar{q}_2) + B\psi_c(\bar{q}_1)\psi_d(\bar{q}_2) \quad (2)$$

an energy eigenvalue measurement with particle one depends on the energy measurement with the other, regardless of their separation in  $L^4$  (this being just a special example of *entanglement* of two presently *non-interacting* quantum entities), where  $|A|^2 + |B|^2 = 1$ . This entanglement *persists* indefinitely until “measurement”  $\Rightarrow$  “Born”  $\Rightarrow$  “collapse of the wavefunction”  $\Rightarrow$  probability ensembles in spacetime,  $L^4$ .

## 2. Explicit Collapse vs. “Magical” Collapse

In explicit collapse models, the standard linear quantum evolution is complemented by (ad hoc) nonlinear terms which become important for macroscopic entities, inducing (stochastic) dynamical collapse, [16–19]. One version uses the already present nonlinearities in non-Abelian quantum field theory [20].

The *disentanglement* in “orthodox” quantum mechanics is only produced by active “measurement” (observation): the “Born rule” and “measurement” on one side,  $\bar{x}_1$ , result in instantaneous “measurement” on the other side,  $\bar{x}_2$ —regardless of spatial distance  $|\bar{x}_1 - \bar{x}_2|$ . This means that the “Born rule” must break relativistic invariance as: (i) “simultaneous events” is not a relativistically invariant concept; and (ii) any arbitrarily small non-zero distance  $\epsilon = |\bar{x}_1 - \bar{x}_2| > 0$  is automatically spacelike (relativistically non-causal) if  $t_1 = t_2$ ; i.e., if the “collapse” is instantaneous.

In dynamical collapse models, energy is not strictly conserved. There exists no continuous Noether symmetry in time, as the dynamical collapse is irreversible. This is side-stepped in “Born” collapse as it is *non-dynamical*—“magical”.

Even if the actual “measurement” is assumed to take a finite time, we still obtain a causal paradox as the “measurement” at the other end is *not* connected to the first by a Lorentz transformation if the opposite ends are spacelike-separated in spacetime [9].

## 3. Linearity vs. Nonlinearity and Locality vs. Non-locality

### 3.1. Quantum Theory

Quantum theory for  $N$ —even non-interacting—spinless quantum entities lives in  $H^{3N}$ , an abstract, complex, *linear* (vector) space. The evolution in  $H^{3N}$  is continuous, linear [21], reversible, non-local (but merely abstractly/implicitly so), and deterministic (describable by differential equations). The wavefunction is not defined until/unless all points in configuration space  $(q_1, \dots, q_{3N})$  are used as input. For  $N > 1$ , quantum theory cannot be embedded in real physical spacetime  $L^4$  [15]. The spacetime description is *only* appropriate for our *detectors and observations* in  $L^4$ —not for the abstract theory supposedly “underlying it all” in  $H^M$ . No quantum fields ever “permeate” spacetime.

### 3.2. Classical Physics

Events define, and also constitute, dynamical classical spacetime,  $L^4$ . The dynamics are continuous, nonlinear, reversible, local, causal, and deterministic (describable by generally relativistic covariant differential equations). These *nonlinear* dynamics evidently *cannot* result from “pure” linear quantum theory alone.

### 3.3. The Magical “Born Rule”

The “Born rule” is *discontinuous*, nonlinear, *irreversible* (entropy-increasing [1]), non-local (explicitly—assumed to be instantaneous in *spacetime*), non-causal, and *postulated* to be intrinsically/fundamentally *random*/probabilistic (e.g., giving no possibility of superluminal *signaling* despite the now physical non-locality in spacetime). It is *not* describable by differential equations or in any other dynamical way, instead being “magical”. Observe that the “Born rule” kills all superpositions (including entanglements), as the end result is a classical *probability*  $\propto |\psi|^2$  and there are no longer any interfering amplitudes/wavefunctions. This also means that there can be no superpositions in spacetime (or of spacetimes), as probabilities do not interfere, only add, forbidding any “quantum spacetime”. It maps  $H^M \xrightarrow{\text{“Born”}} L^4$  into specific *outcomes* (= events) in spacetime,  $L^4$ . Observe that the *eigenvalues* are the physical (and random) “observables” in  $L^4$ , *never* the eigenfunctions themselves (they perpetually live in abstract, complex Hilbert space). Expectation values,  $\langle \hat{O} \rangle = \langle \psi | \hat{O} | \psi \rangle$ , are statistical averages of many measured eigenvalues in identically “prepared” systems,  $|\psi\rangle$ , and are predictable in a statistical sense only.

As Bell showed, *all* measurement results can ultimately be boiled down to *position* results [22], which, together with time, *are* the events in spacetime,  $L^4$ .

A hypothetical free (non-interacting and spinless) single particle can be represented in physical spacetime *only* when  $(q_1, q_2, q_3) = (x, y, z)$  = the location of the *detector* in  $L^4$  upon real “measurement” of the particle, and then by an infinite wave-train with equal probability ( $= 0$ ) of being *anywhere* (upon “measurement”). If instead regarded as semi-localized wave-packets (infinite superposed sums of different wave-trains), they will: (i) disperse and (ii) not have a unique energy or propagation speed, meaning that there would be no reason they should arrive at a detector at a calculable time. Hence, even single quantum “particles” *cannot* travel *through* spacetime as microscopic “bullets”. The momentum “conservation” always assumed (e.g., to ensure spatial correlation of entangled pairs) actually occurs in abstract Hilbert space, *not* physical spacetime. Neither particle in the “pair” exists *anywhere* in spacetime until/unless “measured”. Quantum “particles” have no trajectories in spacetime, and if  $N > 1$ , the evolution *cannot* be embedded in spacetime anyway.

From quantum theory alone, there is thus *no reason* that both “particles” of an entangled pair should be detected simultaneously, equidistant from the source. This can, at best, hold only *in the mean* as: (i) each *individual* measurement event is random (*postulated* so by the “Born” rule) and (ii) the probability of the “Born” rule is the weighted statistical mean of very many individual (random) measured events.

The *locality* assumption only applies to real physical spacetime, *not* to abstract Hilbert space, where obviously everything is non-locally interconnected through the global configuration—i.e., “unmeasured” quantum theory does not respect Lorentz invariance—but this is irrelevant, as Lorentz invariance is only observed in *spacetime* and  $H^M$  itself is *unobservable* in principle.

#### 4. Quantum Space $\neq$ Real Spacetime: Some Physical Consequences

The non-locality in Hilbert space is an abstract, “unphysical”, ever-present, global non-locality. However, it becomes a non-locality in real physical spacetime through “Born’s rule”. The non-locality of measurement is evident already in the one-particle case, as already pointed out very early on by Einstein [23], but it becomes *experimentally testable* in  $N$ -particle entangled states. Originally, tests had  $N = 2$ , [24–29], and *all* “locally real” [30] models formulated in real spacetime,  $L^4$ , are soundly *falsified* by these tests [15], *including* quantum mechanics and quantum field theory *formulated in real spacetime*. Hence, a truly relativistically invariant formulation of quantum theory in *spacetime*, which *includes* “measurement”, could never be compatible with the non-locality of nature already observed in these tests as correlations in real outputs of real experiments in our real world II.

##### 4.1. Consequence One: No “Quantized” General Relativity

Apart from having completely different mathematical structures, quantum theory and general relativity “live” in completely different spaces, which means that “quantum general relativity” and “quantum spacetime” are meaningless concepts [31]. Quantum theory lives in the abstract mathematical linear vector space  $H^M$  with a perfectly deterministic and linear evolution. General relativity lives in, and actually constitutes, real physical four-dimensional spacetime  $L^4$  with nonlinear causal evolution of chains of “events” = the actual “happenings” that constitute the fundamental, irreversible, invariant “constituents” of spacetime, which, when warped by *classical* energy–momentum in *spacetime*,  $T_\nu^\mu$ , results in *classical* gravitation in  $L^4$  through Einstein’s equations  $G_\nu^\mu = \kappa T_\nu^\mu$ .

##### 4.2. Consequence Two: No “Zero-Point Energy” or Cosmological Constant Problem

Virtual “particles” exclusively live in Hilbert space, *not* in physical spacetime. They never manifest in  $L^4$  through the “Born rule”. That is why they are not real. The same applies for the infinite “zero-point energy” of the quantum vacuum in quantum field theory arising from “virtual particles”. This, in turn, explains why the cosmological constant,  $\Lambda$ , does *not* go to infinity and hence why the physical cosmos ( $L^4$ ) has been able to expand leisurely without ripping itself apart.



As “virtual particles” never physically manifest in spacetime, they have no influence at all on the classical energy density  $T_0^0$ , or pressure  $T_i^i$ , in spacetime, and thus *no* effect on the expansion of the universe, as given by Einstein’s equations:  $G_\nu^\mu = \kappa T_\nu^\mu + \Lambda g_\nu^\mu \stackrel{?}{=} \kappa T_\nu^\mu + \kappa \langle 0 | \hat{T}_\nu^\mu(\text{virtual}) | 0 \rangle \equiv \kappa T_\nu^\mu$ . We have here assumed a  $\Lambda$  that is solely due to the presently very fashionable, albeit completely *hypothetical*, “Dark Energy”; i.e., “quantum vacuum”. As  $\Lambda$  in *classical general relativity* is merely a free parameter, we can *choose* for it any value whatsoever to comply with cosmological observations (e.g., finite and *very small*). Such a  $\Lambda_{\text{classical}}$  would give a *curvature* in spacetime even in the absence of  $T_\nu^\mu$  (i.e., in the *classical* vacuum), but  $\Lambda_{\text{classical}}$  is *not* a classical vacuum energy, which by *definition* is identically zero. It is a geometric curvature of empty spacetime itself. In fact, there is *no* instance where this “vacuum energy” is actually physically needed [32–34] (while our argument is based solely on “normal” quantum theory, another, hypothetical and also highly abstract, theory  $\neq L^4$  hints at the same conclusion [35]).

#### 4.3. Consequence Three: Quantum “Particle” Reactions Do Not Happen in Spacetime but in Hilbert Space

Only the *observed*, (“measured”) quantum lives in spacetime, quite contrary to what one might believe when drawing innumerable linearly superposed Feynman diagrams. A particle, in  $L^4$ , *never* occupies two (or more) distinct positions at the same time. The quantum superpositions occur in  $H^M$ , where *no* classical attributes ever manifest. The same goes for “particle” interactions in particle physics, which by definition have  $N > 1$ ; the quantum reactions happen in  $H^\infty$  while the *outcomes* happen in  $L^4$ , and then *only* as a result of the “Born rule”. In the canonical two-slit experiment (e.g., using a laser), each “hit” on the detector screen is the result of a quantum (photon–field) interaction in  $H^\infty$  manifesting as an *event* in  $L^4$  where only *one* discrete, small region of the screen randomly lights up, as if by a photon “particle”. It is only after *many* hits that the superposition (in  $H^\infty$ ) becomes manifested in our real world ( $L^4$ ) as real discrete data patterns through the statistical “Born rule” (Equation (1)).

#### 4.4. Consequence Four: No Black Hole “Information Paradox”

As wavefunctions, for  $N \geq 2$  quantum entities, are objects in Hilbert space with global entanglement through  $(q_1, \dots, q_{3N})$ , *not* in  $L^4$ , they are unaffected by causal horizons in spacetime, meaning that quantum entities inside the horizon are always accessible by entangled quantum entities outside the horizon—nullifying for *quantum theory*, for example, the classical one-way membrane of a black hole event horizon—and hence potential information is in principle always accessible across horizons. A causal probability current in spacetime is definable, and conserved, only for a single, non-interacting particle, making it physically irrelevant. For  $N$  quantum entities, entangled or not, *no* conserved probability current is definable in spacetime and, hence, such a current can never “flow” causally (and neither in Hilbert space, as “probability” requires that the “Born” mapping already have occurred). The abstract non-locality in Hilbert space binds arbitrarily distant quantum entities into a single global irreducible  $\psi$ . The “Born rule” then binds actual events non-locally in real spacetime, regardless of spacetime-interval separation. This resolves the quantum information paradox [36] for black holes, making it a non-question.

### 5. Some Proposed Alternatives to “Orthodox” Quantum Mechanics

#### 5.1. Everett/Many Worlds

Only Hilbert, no collapse [37]. (i) This theory is *linear* and cannot give the nonlinear classical world [21] and (ii) it does not give any probabilities (no “Born rule”), nor does it ever even give any outcomes at all, meaning that a classical world is *absent* in all parallel “universes”.

### 5.2. Explicit Collapse

- (i) *Dynamical* nonlinear collapse. This theory does not give a classical world, as explicit non-locality (in principle) persists in real spacetime and energy is not strictly conserved.
- (ii) Collapse time is *not relativistically invariant*, and cause–effect for entangled systems is ill defined (depends on the frame).

### 5.3. de Broglie–Bohm

No collapse [38–40], everything is (in principle) completely deterministic. (i) This theory does not give a classical world. (ii) Positions for particles always live directly in spacetime and are guided by an *extra* equation; simultaneously, the guiding “pilot wave”,  $\psi$ , lives in Hilbert space. The de Broglie–Bohm theory has *no* need for a “Born rule”, as the classical level is objectively real all the time, but the “pilot wave” guiding the (now objectively real) quantum *particles* is manifestly non-local and lives in unphysical Hilbert space, being eternally global in configuration space. However, as its predictions are designed to be exactly those of orthodox quantum mechanics, it *cannot* explain the nonlinearity of classical physics. Through the guiding equation (which includes  $\psi$ ), the positions of particles in *spacetime* depend on the positions of all other particles (arbitrarily far), making the dynamics in real spacetime also *manifestly* non-local; i.e., it breaks the relativistic invariance of the real world II *explicitly*. In the orthodox theory, it is the “Born rule” in III that saves the real world II from manifestly / deterministically breaking relativistic invariance, as the “Born rule” is only *statistically* non-local in spacetime.

## 6. Summary and Conclusions

“Pure” quantum theory, I, is *implicitly* non-local, but the non-locality is unphysical (not observable) as it does not “live” in spacetime but in Hilbert space.

The “Born rule”, III, is *explicitly* non-local for entangled quantum systems—it correlates spacelike separated *events* in *real* spacetime, as required by Bell’s theorem and its empirically validated requirement of a non-local reality.

“Reality”, II, occurs only in the spacetime of *events* (which are the fundamental “building-blocks” of objective reality), *not* in quantum Hilbert space. Thus, “quantum information” is a misnomer, as information is only manifest in *spacetime* after “*measurement*” (i.e., the “Born rule”, III) has occurred.

The fact that quantum systems with more than one quantum entity  $N > 1$  *cannot* be embedded in spacetime has very deep, profound, and startling consequences. It means, for instance, that quarks and gluons are *not* “constituents” of (e.g.,) protons in *spacetime*, only in abstract, infinite-dimensional Hilbert space [41]—the proton is *not* a “bag” (in spacetime) *containing* quarks and gluons (this is probably the solution to the “proton spin crisis” [42]). More generally, fundamental (quantum) “particle” interactions *never* occur in spacetime: rather, merely abstract quantum fields in  $H^\infty$  result, through the magical “Born rule”, in observed phenomena as objective events in real physical spacetime *interpreted* as particles. Objects in our *real* world  $L^4$  thus do not “consist” of fundamental quantum entities. Not even atoms or molecules “consist” of electrons, protons, and neutrons *in spacetime*; rather, the entangled electron–proton–neutron wavefunction in *Hilbert space* can manifest as events (in  $L^4$ ) interpreted as arising from “atoms” and “molecules” upon “*measurement*”; i.e., upon application of the “Born rule”. Even for superfluids and superconductors, macroscopic in size, the quantum properties perpetually live in  $H^M$  alone. The *observations* of superfluids/conductors are always perfectly mundane events in our normally perceived world. Also, the  $10^{57}$  neutrons in a neutron star live in a configuration space of  $3 \times 10^{57}$  dimensions in Hilbert space (*not* in spacetime), resulting, again and as always, through application of the “Born rule”, in the observed physical properties of the neutron star in  $L^4$  (quarks in quark(-gluon) stars, if they exist at all, would live in  $H^\infty$ ). “Schrödinger’s Cat” [12] is dead *or* alive in our real world II, *after* “Born” III has (“magically”) realized the outcome from its entangled wavefunction in merely abstract Hilbert space I.

The only mystery remaining is why (and how?) the “Born rule” occurs at all; but then again, maybe nature really *is* magical.

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