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The Hidden Clash: Spacetime Outlook and Quantum-State Reductions

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Abstract: It is generally assumed that compatibility with special relativity is guaranteed by the invariance of the fundamental equations of quantum physics under Lorentz transformations and the impossibility of transferring energy or information faster than the speed of light. Despite this, various contradictions persist, which make us suspect the solidity of that compatibility. This paper focuses on collapse theories—although they are not the only way of interpreting quantum theory—in order to examine what seems to be insurmountable difficulties we encounter when trying to construct a space–time picture of such typically quantum processes as state vector reduction or the non-separability of entangled systems. The inescapable nature of such difficulties suggests the need to go further in the search for new formulations that surpass our current conceptions of matter and space–time.

Keywords: space–time; quantum collapse; ontology; quantum superposition; decoherence; entanglement; special relativity; Lorentz invariance

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1. Introduction

From its very origins, it was evident that quantum theory contained elements that were difficult to reconcile with special relativity. The problem is due to an apparent and profound incompatibility of the global conceptions of the universe that the ontological premises of both theories imply. Einstein's theory supported a geometric vision of space–time in which past, present, and future made up a single structure we cannot directly detect by the three-dimensional character of human perception. In total opposition was quantum indeterminism, promoter of an essentially probabilistic reality and, therefore, randomly open to numerous future possibilities. Now, if "future" is a relative term—according to Einstein, what is future for some can be present or past for others—what is the physical meaning of such an indeterminism? At most, it could be considered an expression of our ignorance about the totality of physical events unfolding spatiotemporally. But this clashes head-on with philosophically realistic interpretations that attribute an objective character to quantum probabilities.

The essentially non-relativistic character of elementary quantum theory, which distinguishes time t from the three space coordinates (x, y, z), entailed in a certain way, implicitly admits a concept of absolute simultaneity. This peculiarity is underlined by the fact that, instead of a quantum operator, time corresponds to an ordinary numerical parameter t, just like in classical mechanics. In fact, the existence of a fundamental, continuous and inert space–time, the points of which are specified by space–time coordinates that are classical variables without dispersion (Dirac's "*c numbers*"), is taken for granted in the standard quantum theories. Space–time symmetries are expressed in terms of such coordinates, and quantized dynamic variables are replaced by self-adjoint operators in a Hilbert space. In particular, canonical variables are replaced by operators that obey the typical commutation relations.

The situation becomes very delicate when incorporating special relativity into elementary quantum theory, because then, we are even deprived of the position pseudo-operator used up so far. In a relativistic quantum theory, the concept of a localizable particle—and, therefore, the idea of a wave function carrying its probability density—is even more controversial than in the non-relativistic case [1,2]. In 1949, T.D. Newton and E.P. Wigner published a well-known article [3] in which they showed the practically univocal characterization of a so-called "position" operator on its behavior under space translations and rotations. However, the operator, thus defined, turns out to be non-covariant in the relativistic sense. Furthermore, due to the positive sign of the energy of usual physical systems, if at a certain instant we have an eigenstate of this operator (a "localized state", in the terminology of Newton and Wigner), after an infinitely short time interval that state gets entirely scattered around all over the three-dimensional space. Such unpleasant behavior promoted copious literature about the meaning and real usefulness of the concept of "locatable particle" within the framework of a quantum-relativistic theory. In the case of Dirac spinors corresponding to spin ±½, the Newton-Wigner position operator appears to be identical to the "positional average" operator of Foldy and Wouthuysen [4].

The direct imposition of Lorentz invariance on the Schroedinger equation leads to the Klein–Gordon and Dirac equations. Although these quantum-relativistic equations achieved successes such as the prediction of antimatter and the deduction of spin, their failure was particularly evident when dealing with multi-particle systems. Quantum field theory emerged to remedy this deficiency, in which neither position nor duration are among the basic notions. The main role is played in this context by the quantum field operator, $\Phi(x,\ t)$, which is parameterized by the space–time coordinates considered as classical magnitudes without dispersion (again, Dirac's "*c numbers*"). The dynamic equations of this family of theories are usually obtained from a Lagrangian density—and the action derived from it—conveniently constructed in a way that is manifestly Lorentz invariant. In this way, the equations thus obtained must retain the same form in all inertial frames.

However, neither the primitive quantum-relativistic equations nor the more sophisticated quantum field operators solve the aforementioned difficulties, which exist even without addressing the quantization of gravity. A barely concealed tension persists between the conception of the universe that special relativity defends, as a geometric theory of space–time, and the assumptions about physical reality that support quantum theory in any of its versions. This article will try to expose the insufficiencies of the efforts to incorporate non-relativistic quantum theory into the space–time framework established by special relativity—a problem overshadowed by the search for quantum gravity—highlighting its importance and the little attention it receives. Throughout the entire text, the conceptual aspects of the discussion will be insisted upon, with minimal use of the mathematical apparatus.

In Section 2, we will briefly review the most common interpretations of quantum theory with respect to the type of objects that said theory considers its scope of application, or—loosely expressed—its ontology. Section 3 will examine certain discussions carried out in the specialized literature on the compatibility of some quantum phenomena, such as EPR correlations, and the requirements of special relativity. Sections 4 and 5 will analyze, respectively, in what sense it can be said that the reduction of the state vector and quantum entanglements are incompatible with the space–time of the physical world that special relativity pleads for, although so far there is no satisfactory answer for these questions. Finally, Section 6 will collect some brief conclusions that will put an end to this work.

2. Ontological Commitments of Quantum Physics

The class of objects to which the fundamental terms of a physical theory refer, whatever their ultimate nature may be, is called the "primitive ontology" of that theory[1]. In classical physics, the place of this ontology is occupied by material particles mathematically described by their world lines. In the microworld, we could imagine that classical particles are replaced by a continuous probability distribution related to the quantum wave function [7]. An alternative ontology, developed by Bohm[2] [9–15] with the intention of preserving the basic notion of material particles inherited from pre-quantum physics, makes use of non-local hidden variables that influence the time evolution of the complex wave function expressed by two equations for two real quantities (modulus and phase of the wave function) in order to recover the idea that it is our ignorance of the exact state of the particles, not their intrinsically indefinite character, which reflects the probabilities of the theory [5]. Quantum phenomena are accounted for in Bohm's theory by introducing a quantum potential, whose non-local character [16,17] causes the movement of an elementary particle to be affected by the physical conditions in those regions of space that the particle does not pass through.

But we might also suppose that the genuine being of quantons[3] is best grasped by imagining them as "flashes", or elementary events represented by isolated space–time points [18–20]. In a universe so configured, matter would be nothing more than an accumulation of flashes, and a piece of matter would be but a cluster of such individual points in space–time. The flash ontology is certainly a peculiar choice, since world-lines or fields in space–time are usually chosen for ordinary purposes. The reason backing up this decision lies in the possibility of obtaining—with the proper arrangements in the equations—a spontaneous collapse model based on flashes that is also covariant under the Lorentz transformations. In a model based on this idea, the Bell flashes would form a random set of space–time points whose global distribution would be determined by the initial wave function.

Leaving aside these and other alternatives proposed as a specific ontology for the quantum world, in this work, the premises of a realistic axiomatization of non-relativistic quantum theory will be adopted [21,22]. Such an axiomatization happens to be capable of accommodating the peculiar properties of quantons within a purely realistic approach, and dispenses with mind interventions or a subjectivist interpretation of probabilities. In this formulation, quantons do not necessarily have to acquire sharp values for all their properties. In general, the state of a quantum object σ will be expressed as a linear combination of the eigenfunctions in a certain basis, i.e., $\Psi_\sigma = \Sigma c_j\, \phi_j$. Only in some cases σ will be found in an eigenstate of the considered magnitude and then $\Psi_\sigma = \phi_k$, where ϕ_k is the eigenfunction of that eigenstate. At that moment, we will be able to classically describe such a state since the transition from the classical to the quantum regime has occurred because of the interaction with the environment or with a measuring device.

3. A primer on Quantum Collapses and Entanglement

One of the points historically most debated by physicists and philosophers is related to the character of the so-called "measurement processes" in quantum theory [23]. By measurement, we understand the interaction of a system S with an environment M that, from the correlation between the states of both, allows us to deduce the state of S by observing the state of M. Generally, M is macroscopic and, therefore, liable to be classically treated. As is well-known, Von Neumann had to postulate that, at some point in the measurement process, the system discontinuously passes from a coherent superposition to an incoherent superposition of two states. This is the so-called "projection postulate" or "quantum state vector reduction", which is itself problematic, irrespective of its relativistic implications. This postulate is the origin of the distinction between U processes that evolve in time while continuously and reversibly ruled by the Schroedinger equation and R processes for state function reductions. It is worth emphasizing that, according to Von Neumann, it is in the act of measurement—process R—where a discontinuous, irreversible, and random change occurs in the state function.

Controversy now arises about the moment at which this reduction of the quantum state-vector takes place. Von Neumann seems to suggest that this abrupt change occurs at the moment the observer reads the recording of the measuring device. It is the observer who, upon "seeing" the indications of the pointer "decides", say, that the device is in state φ_k (M) and, therefore, the system S is in state ϕ_k (S). The reduction seems consequently to be triggered by a mental process of the observer, which shrouds this conception of measurement with an unequivocally subjectivist character [24].

In order to solve this problem, we have interpretations based on the objective collapse of the function Ψ, which reject the assumption of linearity in the evolution of the state function. Dynamical equations are often rewritten so that they are sensitive to certain threshold values of the number of particles or the mass density in a quantum system. Exceeding these thresholds naturally causes the collapse of the state function. The most developed proposal of this kind (known as GRW theory) is due to Ghirardi, Rimini, and Weber [25–29]. But obviously, this approach poses the question about the reference frame in which that objective collapse occurs and fuels the debate on the possibility to coherently insert quantum events in our physical space–time.

The GRW theory slightly differs from the quantum case in its predictions about the results of particle diffraction and interference experiments, although some neutron diffraction experiments carried out to decide the question [30] seem to favor ordinary quantum theory. Despite this growing evidence, there are still many researchers convinced that some modification of this idea will provide the appropriate answers to free us from the annoying collapse of the wave function [31]. Among the latter is the American physicist Wojcieh Zurek, a notorious partisan of the so-called "environmentally induced superselection".

Zurek assumes that the immense number of degrees of freedom in the environment of any microsystem is what causes the linear superposition of quantum states described by the wave function to evolve very quickly towards a single state coinciding with the classical result that is, in fact, obtained. Thus, for a mass of one gram, the interference terms of its wave function would decrease about 10^{431} times in a billionth of a second. This would explain why the quantum effects, typical of the ultramicroscopic scale, are not macroscopically appreciated. However, the reason why superselection eliminates all possible states except the only one that is actually detected is not rightfully explained.

Nevertheless, we cannot omit the influence of the relativity view on this problem, which becomes even more intricate when we enter the entanglement phenomena. At the end of the 20th century, experimental evidence put forward the existence of unequivocal correlations between spatially separated events in a relativistic sense [32,33], that is to say, events that cannot be connected by light signals. Since such experiences were based on a discussion of the conceptual foundations of quantum theory posed by Einstein, Podolsky, and Rosen, it seems natural to abbreviate the name "non-local quantum correlations" simply as EPR correlations.

What has often been considered the hallmark of quantum theory is the fact that any pair of initially independent systems, S_1 and S_2, can constitute "entangled" states, $S_1 \oplus S_2$. In those entanglements, the component subsystems lack their own state vector, and the probabilities assigned to pairs of measurements—one on each system—cannot be factored as the product of two separate probabilities corresponding to each subsystem. This type of state was described by Schrodinger as the characteristic feature of quantum mechanics, which forces a complete departure from classical lines of thought.

Tim Maudlin openly wondered about the compatibility between Einstein's relativity and the basic traits of the quantum world in some renowned texts [34,35] on the subject. After adopting a loose notion of what causal connections are, he came to the conclusion that quantum entanglement does manifest a type of non-local causality equivalent to the transmission of faster-than-light signals, although the paradoxes that causal-loops can bring about are excluded due to the impossibility of controlling these non-local correlations. Other authors showed their reluctance at the lightness with which Maudlin expanded the concept of cause, pointing out that in any case, the EPR correlations would show a type of link that is both non-local and non-causal.

Another path through these issues was opened in the second half of the twentieth century in the wake of a new approach, the superfluid vacuum theory, which suggested that, because of the uncertainty principle, the state of motion of the ether can only be specified by a wave function [36–38]. Afterwards, the idea of regarding a vacuum as a non-relativistic superfluid whose excitations give rise to relativistic space–time made its way into the scientific community. Superfluid vacuum theory proposes that a physical vacuum is not empty but filled with a superfluid medium, often referred to as “ether”, that exhibits properties analogous to those of conventional superfluids, such as zero viscosity and irrotational flow. Within this framework, particles arise as quantized excitations or disturbances in the superfluid medium, akin to quasiparticles in condensed matter systems [39,40]. One of the key insights of superfluid vacuum is the possibility to reconcile the discreteness of quantum theory with the continuous space–time of special relativity. In this theory vacuum behaves as a superfluid that can undergo phase transitions, leading simultaneously to the emergence of discrete quanta and the continuous fabric of space–time.

This theory also suggests that collapse of the wave function arises from the interaction between the observed system and the vacuum medium. In this view, the act of measurement disturbs the equilibrium of the vacuum, causing the collapse of the wave function and the emergence of a definite outcome, and the apparent non-locality of quantum collapse arises from the interconnected nature of the vacuum medium, rather than from instantaneous action-at-a-distance. One of the key insights of the superfluid vacuum theory is that while the superfluid background may be non-relativistic, particle-like small fluctuations of it obey the Lorentz symmetry. This means that these fluctuations—that is to say, the effective action associated with them—exhibit the same patterns of behavior under boosts and rotations as particles moving at relativistic speeds. This surprising result suggests that there may be a fundamental connection between the non-relativistic superfluid background and the relativistic behavior of particles. However, the mathematical formalism of the superfluid vacuum theory is still under development, requiring further refinement and extension to encompass the full range of physical phenomena [41–43].

4. Problems in a Space–Time View of State-Vector Reductions

Just purporting to be upfront, we should notice that the question here addressed naturally emerges within the standard formulation of quantum theory, despite the fact that there exist other theoretical interpretations that plunge away that issue rather than solving it. Quantum systems are widely represented by density operators or state-vectors—traditionally called “wave functions”—in a Hilbert space, and their evolution takes place in that same abstract setting (although configuration space seems to be not so hard to relate to classical space). Nevertheless, Hilbert space is in no way directly related to our familiar space–time in which the principles of special relativity apply. There is no path to obtain space–time as the limiting case of a Hilbert space. And just from this issue, there arises the essential difficulty of conceiving the reduction of the wave function as a physical process in a certain space–time framework. We must not forget that a function Ψ that is written as a superposition in a certain basis does not have to be also developed as a linear combination in a different basis. For example, a state function that happens to be an eigenfunction of the spin operator on the x-axis with an eigenvalue −½ will be generally expressed as superposition of the eigenfunctions whose eigenvalues +½ and −½ on the z-axis. So that, if we attribute an objective physical reality to the state function collapse, we must decide on what basis it occurs.

Quantum diffraction experiments through a slit are explained by the broadening in space of the probability amplitude represented by the wave function. However, when an interaction occurs (a possible “measurement”), such as the darkening of a specific point on a photographic plate located behind the slit, for example, the wave function instantly cancels out—collapses—throughout all space. Similarly, a measurement made on one member of a pair of entangled quantons collapses the superposition and changes the state of the other component. The dilemma is obvious: how can these collapses be expressed in terms of a coherent space–time picture? Is its instantaneous and non-local nature acceptable in a relativistic context?

The interpretations of quantum physics that try to solve the measurement problem do not prevent a violation of Lorentz invariance, because, in fact, any type of collapse—spontaneous or induced—would occur at different times depending on the chosen reference frame. If we restrict its meaning, Lorentzian invariance would affect only the dynamical laws that rule the behavior of matter and radiation, and not the structure of space–time itself. On this view, Lorentz invariance is not a space–time symmetry, but rather a purely dynamic one. And since the behavior of matter and radiation in different reference frames obeys the Lorentz transformations, this point of view is empirically suitable. However, Lorentzian theories of this type suffer from a serious formal defect since they cannot accurately reflect space–time symmetries as special relativity does. Paraphrasing Einstein, we could say that in this perspective we find theoretical asymmetries that do not seem to exist in the phenomena. This is the main reason—set aside mere logical economy—that invites us to abandon Lorentz's approach in favor of Einstein's [44,45].

More confusion is caused by the participation in the debate of atypical readings of Lorentz invariance, called "theories with hyperplane dependence". The equivalence, or covariance, of physical laws in all inertial reference frames constitutes one of the basic assumptions of special relativistic theory. To relate the expressions of these laws between different inertial frames, the rules are no other than the Lorentz transformations, which manifest the geometric symmetries of Minkowski space–time and exclude physical processes that do not respect them. By applying a Lorentz transformation, we transfer our perspective of the world from a certain inertial system, which splits space–time into a three-space surface and an associated time axis, to another inertial frame with its own space–time foliation. In fact, any given space–time point P can be endowed with many different values of the variable t to play the role of its present, every one of them corresponding to the various hypersurfaces containing P.

Notwithstanding, in the neighborhood of space–time regions in which a collapse of the wave function occurs, it is impossible to coherently apply the Lorentz transformations. Pure and simple, we cannot carry out a transformation from a hyperplane of simultaneity for which the collapse is located in its future to another hyperplane with respect to which the same collapse is in the past without many troubles associated with the space–time interpretation of that collapse itself. Furthermore, as already noted, the collapse of the quantum state takes place instantaneously at all points of the hyperplane of simultaneity associated with every inertial frame. The attempt to manage the entanglement by imposing a privileged foliation in the relativistic space–time would spoil the theory with asymmetries without any counterpart in the real phenomena[4] [47,48].

The issues become more serious when we try to combine the perspectives on the time variable offered by special relativity (there is no genuine "time flow", since events form series—world-lines—causally connected in the Minkowskian space–time) and quantum theory (objective probabilities are assigned to unpredictable random events). For the sake of clarity, let us assume that at a time t a radioactive atom has, according to our calculations, a probability equal to 0.5 of disintegrating the next day. Now, such a statement only makes sense if, at instant t, there is no future predetermined by the Minkowski geometry that supports special relativity. If we had a complete space–time picture in which that atom gets disintegrated after twenty-four hours from t, the aforesaid probability—regarded as an objective property of the physical phenomenon—would lose its genuine meaning.

The answer to this dilemma does not seem so simple if we think of a pair of observers, A and B, as described by special relativity. Suppose that B moves with respect to the radioactive atom in such a way that, since decay has not occurred for it, its hyperplane of simultaneity allows it to assign a probability of decay equal to 0.5 at time t. But if A moves appropriately, its simultaneity hyperplane will intersect the world line of the radioactive atom in the future of B. Then, for A at the instant t' of its own frame, the atom will remain intact or will be disintegrated, and will therefore assign a probability of 0 or 1 for each event. Everything indicates, apparently, that A and B will not coincide in the probability distributions attributed to the same phenomena [34,35,49,50], even when their inertial frames are perfectly equivalent from a relativistic perspective.

In somewhat more technical language, we know that each inertial frame selects a space hyperplane of simultaneity in the relativistic Minkowskian space–time. We also know that in any of those hyperplanes, the state function Ψ defines a probability distribution

$\rho_\psi = |\Psi|^2$. But if there is no privileged hyperplane that justifies the notion of "absolute simultaneity", and given that, in general, the different calculations carried out in different simultaneity planes will not agree, there remains the question about the hyperplane on which we should evaluate $|\Psi|^2$.

In short, either a realistic view of the predictions of quantum theory is abandoned, or our ideas about special relativity must be modified by accepting a privileged space–time foliation. Whether observer A or B, only one of them has the correct physical perspective; only one "sees"—so to speak—what really happens. The drawback of this option is that it favors the point of view of one of the frames without apparently having compelling reasons to do so.

On the contrary, if we adopt a different Ψ for every observer, the collapse is now conceived as a mere formal construct, a pseudo-event that takes place when the observer's knowledge about the system changes. Only when we attribute objective features to Ψ and demand that its collapse be consistent with other physical laws established in a single universe do paradoxes and contradictions arise. However, on the one hand, Everett's many-worlds interpretation [51–53] presupposes the unrestricted validity of the usual quantum theory in all ranges of distances and sizes, a risky hypothesis to say the least. On the other hand, the subjective interpretation of Ψ drags us to an idealistic conception of quantum phenomena that has little relationship with the usual convictions and practices of researchers dedicated to this field.

It is ordinarily accepted that a certain property represented by an operator $\hat{w}$ will possess an eigenvalue ω_k if, and only if, the quantum state $|\psi\rangle$ satisfies the equality $\hat{w}\ |\psi\rangle = \omega_k\ |\psi\rangle$. Taking a local region in space–time, Ω, that contains a system or physical object capable of being in the eigenstate $|\psi\rangle$, we face two possibilities: either the eigenvalue ω_k depends on the hypersurface that contains Ω, or it is an absolute property, dependent only on Ω and not on the hyperplanes in which that region is included [26,54–56]. According to special relativity, different frames in relative inertial motion would assign to the different points of a quanton's world-line different probabilities for the result of a measurement, depending on whether the simultaneity planes associated with every frame are in the future or in the past of that measurement. In this situation, the prone interpretation of probability—as said before—is stripped of its greatest appeal in a relativistic context. We can no longer consider quantum probabilities to be inherent properties of a microphysical object, such as its electric charge or its spin, but rather features partially dependent on the space–time framework chosen for its description.

By introducing relativistic covariance into elementary quantum theory, upon requiring that the coordinates be subjected to Lorentz transformations, we conclude that different inertial observers will claim that the reduction of the state vector, $\boldsymbol{R}$, occurs at different instants depending on their own time scales. But this does not make any sense because the $\boldsymbol{R}$ process is probabilistic itself, and probabilities are not invariant magnitudes (like Minkowski intervals or the modulus of any other four-dimensional vector) under relativistic coordinate transformations Maxwell (1985) [57]. The crux of the matter is that the $\boldsymbol{R}$ process lacks a description in terms of the space–time geometry of special relativity. And this is not an obstacle that can be easily avoided since it represents the basic nature of quantons. It is physically incongruous for an inertial observer to maintain that Ψ is a linear combination of states, while another one replies that in another frame Ψ is equal to a single eigenstate. The one and the same physical object existing in reality cannot belong to different ontological categories for inertial observers who, according to Einstein's theory, must obtain mutually coherent images of the universe.

It is hard to exaggerate the critical importance of this point: the reason for all these difficulties, in short, is that the probability distributions necessary in quantum theory lack a 4-dimensional geometric translation that allows us to construct any space–time picture of the evolution of quantum objects in the same sense in which that image does exist for classical particles and fields. Quantum probabilities, whether interpreted objectively or subjectively, cannot be easily geometrized to seek a coherent link with the properties of space–time. This is an aspect that neither Maudlin nor other authors have properly addressed because it is a question that, in principle, seems to have no solution within the framework of both—relativistic and quantum—theories that are now well consolidated.

5. The Relativistic Issues of EPR Correlations

Entangled states retain their character even when the spatial separation between the component subsystems becomes arbitrarily large. This has been verified experimentally even with photons several kilometers apart [58]. Empirical evidence compels us to admit, beyond any doubt, that physical objects located in different parts of space cannot be considered entirely independent of each other [59,60]. Despite this, EPR correlations should not be understood as mysterious remote actions that bring about simultaneous changes between separate systems. Causal processes would be those that possess and transmit a conserved physical magnitude, and in turn an interaction would be an exchange of such globally conserved quantities. These conditions are not met in the EPR correlations [61–63], which therefore cannot be really considered actions-at-a-distance. The discussion of faster-than-light actions at a distance only arises when we assume, contrary to the premises of quantum theory, that each quanton has a well-defined spin state prior to measurement.

Expressed more formally, each open space–time region, O, is usually associated with an algebra of operators, $\Gamma(O)$, whose self-adjoint members correspond to the observable magnitudes by means of operations[5] confined to the region O. Given two bounded disjoint regions, O_1 and O_2, the physical processes in the region $O_1 \cup O_2$ are not univocally determined, in general, by solely indicating the values of all local magnitudes in O_1 and O_2—quantities represented by operators $\Gamma(O_1)$ and $\Gamma(O_2)$—that have sharp values. In addition, we must specify the values of the quantities represented by operators in $\Gamma(O_1 \cup O_2)$. It is simply not true that the behavior of all objects in the physical world is deducible from local properties belonging to points or tiny bounded regions of space–time.

Let us now try to obtain a foliation in Minkowski space–time that serves for an adequate description of quantum processes such as entanglements and EPR correlations. To this purpose, it seems essential to satisfy a list of conditions:

(1) all processes in the physical world must be capable of being described as a succession of states contained in that foliation;
(2) no foliation should be privileged in the sense of containing the only correct series of states;
(3) the differences between series assigned to different foliations must be attributed entirely to the fact that the various foliations compile the points of space–time in a different way, thus forming the hypersurfaces of simultaneity in which the quantum states are defined;
(4) once the complete series of states of a quantum process is given in a certain foliation, the homologous series (corresponding to the same process) in other foliations are uniquely determined.

A local observable is anything that can be subjected to observations within a space–time region as small as wanted. On the contrary, a global property is one that, at least in some cases, is not reducible to an arbitrarily small region. It would be, for example, the center of mass of a spatially-extended mass distribution defined on a hypersurface Σ. This property is assigned to a point of Σ, and that is why we say that it is located there, although it is not inferred from local observations in the sense previously described[6] in restricted space–time regions that contain that point [66–68].

However, suppose that for each foliation of space–time we have a series of states that encompass all physical events along the successive hypersurfaces that constitute the foliation itself. The challenge now would be to accommodate the notion of reduction of the state function in such an image of reality without sacrificing, among the conditions listed above, either the second (there are no privileged foliations that provide the only correct series of states) or the third one (the differences between the series of states contained in various foliations are due entirely to the fact that different foliations locally rearrange the series differently). According to the ideas defended by Aharonov and Albert [69] in each foliation the collapse of the state function occurs in the hypersurface that contains the event that we call "measurement" or, in general, "interaction". The suggestion is reasonable insofar as it supposes that collapses occur in a certain closed space–time region[7] Ω. If Ω is in the future of a given hypersurface Σ, the state function in Σ will represent a superposition without collapsing. When Ω is located in the past of Σ, the state function in Σ will have already collapsed. What happens to the state function on a surface that precisely intersects the region Ω is a more delicate question that depends on the concrete details of the collapse process supported by the theory in use [26,49,56,70,71].

In Galilean space–time, with a distinguished foliation over the concept of absolute time, the computation of intermediate states between two given instants is unambiguous. In a relativistic framework, however, given two points A and A' on the world-line of an object, how to select the events on which the evolution of the stochastic function depends in order to obtain the appropriate probabilities of the different events after A, including A' itself? It is not clear, for example, whether we should include events that are spatially separated—and which ones—from the one whose probability we are trying to calculate. In any case, for each space hypersurface Σ, we will have a probability distribution P_Σ conditioned by all the events belonging to the past of Σ. This is why we need to specify the space hypersurface to which we refer when we seek to calculate the probability of a certain state in a system S within a space–time region Ω. It is essential to know on which events our conditional probability depends, since the probabilities specified from Σ are conditioned by the entire past of Σ.

Standard quantum dynamics teaches us that a state vector at a time t_1, $u(t_1)$, changes to a vector $u(t_2)$ at a later time t_2, as the Schroedinger equation shows. The use of phrases such as "instant t_1" or "instant t_2" presupposes, of course, a certain reference frame with respect to which we specify durations. Consequently, the state of the quantum at an instant t with respect to a frame f will consist of a probability distribution defined on a hyperplane of simultaneity of f. In another inertial frame, f', we will have other probability distributions in their own simultaneity hyperplanes, related to those of f by the appropriate transformation equations. According to this view, the spin values of photons used in EPR experiments—for example—are considered properties relative to a certain reference frame, or more specifically, relative to a specified spatial hyperplane. Consequently, the search for a reconciliation between quantum non-separability and relativistic locality leads us to consider the properties affected by quantum entanglement, not as intrinsic features of micro-objects, but as relational properties (i.e., properties that acquire their meaning in relation to something external to the object that possesses them).

We would need to ensure adequate covariance of Ψ when transforming between inertial reference frames, a rule for calculating transition probabilities, and an evolution equation for Ψ (except, perhaps, during collapse). Likewise, when Ψ were the eigenstate of a certain operator, the probability of obtaining the corresponding eigenvalue should be equal to 1. Can we then define a complete set of commutable operators using the space–time symmetries of the Lorentz transformations? If the answer is negative, it will not be possible to define the physical state of a system by means of an eigenfunction common to all these operators. Once again, the source of the greatest ambiguities lies in the freedom of the different inertial observers to define their own space hypersurfaces of simultaneity. With this, in every inertial reference frame we will obtain different probability distributions for the same quantum process. The debate has become so intricate that some authors consider it to be a poorly posed question and maintain that it proves the impossibility of constructing a relativistic quantum mechanics of localizable particles without also including physical influences (*not* EPR correlations) faster than light [1].

The question is, then, can a process like state vector reduction satisfy conditions of local evolution while preserving an acceptable notion of quantum probability? Here the word "acceptable" implies compliance with the non-signaling theorem, so that EPR correlations do not allow sending signals faster than light or establishing simultaneity relationships at a distance [28,72]. The core of the conceptual—although not empirical—incompatibility between both theories lies in the fact that special relativity advocates a static image of space–time, which hardly matches the assignment of objective and non-trivial probabilities to quantum phenomena [73–75]. Moreover, if quantum probabilities are objective properties of quantons—the so-called propensities—it is not easy to understand how their determination can depend on the space–time perspective of the observer. In different reference frames, the same stage of a quantum system evolution will be tied to different instants of time, and therefore different probabilities will be assigned to it. That situation seems to break the notion of propensity as an objective physical property [76–80] on an equal footing with energy, electric charge, or spin.

A crucial ingredient in this construction is the objectivity of quantum probabilities, whose values appear to be different in each reference system and also evolve over time. At every instant t, there exists a random function, P_t, that assigns a certain probability of occurrence to each possible past, present, or future event. The probabilistic distribution $P_t{}'$ corresponding to a time t', after t, is obtained by imposing on P_t conditions dependent on the complete series of states of the system between t and t'. It could be objected that the totality of the "histories" (complete series of states) of a system between two given instants forms an infinite, non-countable set. Therefore, it would be impossible—at least in the usual definition of probability—to assign a non-zero probabilistic value to any individual story. There are two escape routes from this dilemma: either we alter the ordinary notion of conditional probability, or we establish appropriate restrictions on the domain of our probability function [81], but none of them seems to be fully satisfactory. In fact, the relation between propensities and probabilities is still a matter of intense debate [82,83].

In the context of quantum mechanics, propensities are often interpreted as intrinsic tendencies of systems to evolve in a certain way. These propensities are thought to determine the probability of different outcomes in a quantum measurement. However, in a relativistic framework, the perception of these propensities may vary depending on the reference frame of the observer. This raises serious concerns not only about the universal validity of quantum probabilities but also compels us to wonder how they might be affected by relativistic effects such as time dilation and length contraction. One way to address these challenges is to consider the role of symmetries in shaping the probabilities of quantum events across different reference frames. Symmetries, such as rotational symmetry and Lorentz symmetry, play a crucial role in defining the laws of nature and ensuring their invariance under different coordinate systems. By studying the symmetries of the underlying quantum theory, we can gain insights into the constraints on probability ascription from various reference frames. These symmetries may provide a framework for understanding how probabilities are transformed across different reference frames and how they can be reconciled with the principles of relativity. Nonetheless, it is, *a priori*, a very delicate matter since probability is a non-geometric magnitude extremely difficult to fit into relativistic space–time.

Not only that, but we would also encounter a serious obstacle in the case of finding a probability distribution dependent on the reference frame. We would have to face two equally uncomfortable situations, the first of which, for an observer, would be a self-state of the quantum system in a certain frame, which could be a superposition of states in another inertial frame. For different inertial observers, this disparity would imply that the world stuff content would be categorically different in an ontological sense. We should not forget that σ_q and σ_c are states whose ontological status radically differ from each other. It does not seem metaphysically legitimate to construct a physical theory under such conditions. But even in the case in which two inertial observers agree that the same quantum system is in a superposition state, they would not necessarily agree on the value of the probability amplitudes that define the participation of every eigenstate in the superposition. This raises new questions that we are not even sure we know how to formulate correctly. For the time being, no definite answer is available to those profound queries [57,84–86].

Serious problems arise again in the attempt to associate a space–time image with the phenomena of quantum entanglement and correlations of the EPR type. If we let the pair of quantons move far away enough—for example—their separation will be spatial, and no physical signal could connect them because, in order to do so, they would have to travel at a speed higher than that of light. In that case, the chronological order of physical events depends entirely on the reference frame from which it is viewed. And as long as we decide to carry out a measurement on one of the quantons, this ambiguity in the space–time order will have frankly disturbing consequences.

An observer could say that when we measure the state of one of the quantons, the $\boldsymbol{R}$ process that collapses its wave function also collapses that of the other quanton, regardless of the distance, which is true and constitutes the essence of quantum entanglement. However, another observer moving in a different way would have the right to say that, in his frame, the order of events is different: firstly, the wave function of the second quantum collapses—the one we have not measured—and then we are the ones who carry out the measure on what we have previously called the first quanton.

This second perspective would be perfectly legitimate from the point of view of special relativity, although it violates all rules of entanglement, an essential characteristic of quantum theory. A function Ψ that evolves in time following a process $\boldsymbol{U}$, without an interaction with the macroscopic environment (usually called "measurement"), cannot spontaneously collapse and give rise to a process $\boldsymbol{R}$ by itself. It is plainly true that we do not fully understand the mechanisms involved in $\boldsymbol{R}$ processes—which has opened very interesting lines of research—but it is equally true that there is an ontological difference between systems in a state of superposition and those in an eigenstate [23,87–89].

This is the arrow that points to the heart of a controversy that is almost always ignored. Condensing special relativity into two statements, they could be summarized as follows: (1st) the speed of light is a universal constant that nothing can exceed; (2nd) the descriptions of the universe corresponding to different inertial frames must be compatible with each other. Well, in view of what has been stated so far, the relativistic formulation of a quantum theory for particles without interaction obeys the first requirement and fails to comply with the second. That is the root of a latent confrontation between quantum theory and special relativity that is almost always tiptoed around. Needless to say, the solutions proposed to date [49,90–96] (admitting privileged frames, external parameters that mimic Newtonian "absolute time", or ramifications in space–time) have not significantly clarified the enigma.

6. Conclusions

The reconciliation between quantum theory and special relativity is a problem usually regarded as solved in order to focus all the efforts on the search for a quantum version of gravitation. However, a closer look reveals that in this domain there are still profound setbacks pending clarification. When we try to immerse quantum theory in a relativistic formulation, the requirements for space–time covariance become so demanding that we end up crossing the borders of quantum field theory, conceived as the royal road for the insertion of relativistic covariance in the quantum world. That is, at least, the general consensus, even though, in fact, it suffers from its own and not insignificant drawbacks.

Any realistic ontology we choose will agree on the radical difference between a quantum superposition and an eigenstate, a difference linked to the transition between the classical and quantum worlds that still awaits a complete and satisfactory explanation. Regardless of the mechanism that produces it, the reduction of the state-vector of a quantum system is essentially non-relativistic since it presupposes a single time variable for all observers and handles a concept of probability that only makes full sense by renouncing any space–time description of the aforementioned process. Probability is not a space–time magnitude capable of being covariantly expressed under the Lorentz transformations, which prevents attributing to probability distributions the objective character possessed in special relativity by other 4-dimensional quantities. The fact that different inertial frames assign different instants to the reduction of the state-vector of a quantum system implies that the content of the universe in these frames will belong to antagonistic ontological categories (superposition of states or eigenstate), which does not occur in any other physical theory.

The obstacles get worse when we include EPR correlations between pairs of quantons in a state of quantum entanglement. In that case, the relativity of time leads to different inertial frames disagreeing about the chronological order in which there happen the events associated with the reduction of the state-vector in one of the members of the entangled couple, when it is measured, and the corresponding modification in the value of that very property in the other member of the couple. This discrepancy violates the essential core of the evolution laws of evolution of quantum systems and renders mutually incompatible images of the universe (in a deep ontological and nomological sense) depending on the chosen frame. This incompatibility is not overcome by the fact that quantum entanglement is certainly incapable of transmitting energy or information faster than the speed of light.

Perhaps the real solution lies in a greater openness of mind to more radical redefinitions of the physical world. Maybe what we believe to be spatially separated elementary particles are nothing more than superficial manifestations of physical entities yet to be elucidated, and perhaps our notions of space and time are derivable in some sense from them. These entities—despite their very high degree of abstraction—would ultimately correspond to the "elements of reality" to which Einstein, Podolsky and Rosen alluded in their famous article. These would be pregeometric ingredients that would refer to a genuinely primitive and deeper structural level than those of "space–time event" or "quantum state". Truly, that has been the aim to which all the attempts carried out at the end of the 20th century were headed; that is, on the possibility of deducing the concepts of matter, space, and time starting from more primordial elements. Even if their efforts were not crowned with success, the path remains open for those who wish to accept the challenge.

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Notes

[1] Dürr, Goldstein and Zanghì [5]. Bell [6] preferred to speak of "local beables".

[2] The problem of finding a covariant quantum theory under the Lorentz transformations that has Bohm's theory as a non-relativistic limit has proven to be extremely thorny. See, for example, Berndl et al. [8].

[3] From now on we will use the word "quanton" to refer to quantum objects, thus avoiding any etymological association with waves or corpuscles.

[4] The dynamics of collapse in GRW theories is not Lorentz invariant either. See Albert [46].

[5] Kraus [64] argues that any physically possible interaction can be symbolized by a positive definite linear mapping of the set of null trace operators onto itself. He also showed that every function φ is represented by a countable set of operators, {K i }, the Kraus operators. Thus, the Kraus representation of the usual unitary evolution consists of a single unitary Kraus operator.

[6] Fleming and Butterfield [65] argue that the Newton-Wigner position operators are localized in the same way but not locally definable.

[7] "Closed" in the topological sense: the border points also belong to the set.

References

1. Malament, D.B. In Defense of Dogma: Why There Cannot Be a Relativistic Quantum Mechanics of (Localizable) Particles. In *Perspectives on Quantum Reality: Non-Relativistic, Relativistic, and Field-Theoretic, 1–10*; Clifton, R., Ed.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1996.
2. Halvorson, H.; Clifton, R. No Place for Particles in Relativistic Quantum Theory? *Philos. Sci.* **2002**, *69*, 1–28. [CrossRef]
3. Newton, T.D.; Wigner, E.P. Localized States for Elementary Systems. *Rev. Mod. Phys.* **1949**, *21*, 400–406. [CrossRef]

4. Foldy, L.L.; Wouthuysen, S.A. On the Dirac Theory of Spin 1/2 Particles and Its Non-Relativistic Limit. *Phys. Rev.* **1950**, *78*, 29–36. [CrossRef]
5. Dürr, D.; Goldstein, S.; Zanghì, N. Quantum Equilibrium and the Role of Operators as Observables in Quantum Theory. *J. Stat. Phys.* **2004**, *116*, 959–1055. [CrossRef]
6. Bell, J.S. The Theory of Local Beables. *Epistemol. Lett.* **1975**, *9*, 11–23.
7. Ghirardi, G.C.; Grassi, R.; Benatti, F. Describing the macroscopic world: Closing the circle within the dynamical reduction program. *Found. Phys.* **1995**, *25*, 5–38. [CrossRef]
8. Berndl, K.; Dürr, D.; Goldstein, S.; Zanghì, N. Nonlocality, Lorentz invariance, and Bohmian quantum theory. *Phys. Rev. A* **1996**, *53*, 2062–2073. [CrossRef] [PubMed]
9. Bohm, D. A Suggested Interpretation of the Quantum Theory in Terms of "Hidden" Variables. Part I and II. *Phys. Rev.* **1952**, *85*, 166–179+180–193. [CrossRef]
10. Valentini, A. Signal-locality, uncertainty, and the subquantum H-theorem. I. *Phys. Lett. A* **1991**, *156*, 5–11. [CrossRef]
11. Valentini, A. Signal-locality, uncertainty, and the subquantum H-theorem. II. *Phys. Lett. A* **1991**, *158*, 1–8. [CrossRef]
12. Bohm, D.; Hiley, B.J.; Goldstein, S. The Undivided Universe: An Ontological Interpretation of Quantum Theory. *Phys. Today* **1993**, *47*, 90. [CrossRef]
13. Cushing, J.T. *Quantum Mechanics*; Chicago University Press: Chicago, IL, USA, 1994.
14. Callender, C.; Weingard, R. Trouble in Paradise? Problems for Bohm's Theory. *Monist* **1997**, *80*, 24–43. [CrossRef]
15. Dürr, D.; Goldstein, S.; Tumulka, R.; Zanghì, N. Bohmian Mechanics and Quantum Field Theory. *Phys. Rev. Lett.* **2003**, *93*, 090402. [CrossRef]
16. Baublitz, M.; Shimony, A. Tension in Bohm's interpretation of quantum mechanics. In *Bohmian Mechanics and Quantum Mechanics: An Appraisal*; Cushing, J., Fine, A., Goldstein, S., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1996; pp. 251–264.
17. Bohm, D.; Bub, J. A Proposed Solution of the Measurement Problem in Quantum Mechanics by a Hidden Variable Theory. *Rev. Mod. Phys.* **1966**, *38*, 453–469. [CrossRef]
18. Bell, J.S. Towards An Exact Quantum Mechanics. In *Themes in Contemporary Physics—II*; Deser, S., Finkelstein, R.J., Eds.; World Scientific: Teaneck, NJ, USA, 1989; pp. 1–26.
19. Bell, J.S. Against "measurement". In *Sixty-Two Years of Uncertainty: Historical, Philosophical, and Physical Inquiries into the Foundations of Quantum Mechanics*; Miller, A., Ed.; Plenum Press: New York, NY, USA, 1990; pp. 17–31.
20. Kent, A. "Quantum jumps" and indistinguishability. *Mod. Phys. Lett. A* **1989**, *4*, 1839–1845. [CrossRef]
21. Pérez-Bergliaffa, S.E.; Vucetich, H.; Romero, G.E. Axiomatic foundations of nonrelativistic quantum mechanics: A realistic approach. *Int. J. Theor. Phys.* **1993**, *32*, 1507–1522. [CrossRef]
22. Perez-Bergliaffa, S.E.; Romero, G.E.; Vucetich, H. Axiomatic foundations of quantum mechanics revisited: The case for systems. *Int. J. Theor. Phys.* **1996**, *35*, 1805–1819. [CrossRef]
23. Stapp, H.P. S-Matrix Interpretation of Quantum Theory. *Phys. Rev.* **1971**, *D3*, 1303–1320. [CrossRef]
24. London, F.; Bauer, E. *La Théorie de L'Observation en Mécanique Quantique*; Hermann: Paris, France, 1939.
25. Ghirardi, G. Properties and events in a relativistic context: Revisiting the dynamical reduction program. *Found. Phys. Lett.* **1996**, *9*, 313–355. [CrossRef]
26. Ghirardi, G. Local Measurements of Nonlocal Observables and the Relativistic Reduction Process. *Found. Phys.* **2000**, *30*, 1337–1385. [CrossRef]
27. Ghirardi, G.C.; Grassi, R.; Pearle, P. Relativistic dynamical reduction models: General framework and examples. *Found. Phys.* **1990**, *20*, 1271–1316. [CrossRef]
28. Ghirardi, G.C.; Rimini, A.; Weber, T. A General argument against superluminal transmission through the quantum-mechanical measurement process. *Lett. Nuovo C.* **1980**, *27*, 293. [CrossRef]
29. Ghirardi, G.C.; Rimini, A.; Weber, T. Unified dynamics for microscopic and macroscopic systems. *Phys. Rev. D* **1986**, *34*, 470. [CrossRef] [PubMed]
30. Zeilinger, A.; Gähler, R.; Shull, C.G.; Treimer, W.; Mampe, W. Single- and double-slit diffraction of neutrons. *Rev. Mod. Phys.* **1988**, *60*, 1067–1073. [CrossRef]
31. Pearle, P. Combining stochastic dynamical state-vector reduction with spontaneous localization. *Phys. Rev. A* **1989**, *39*, 2277–2289. [CrossRef] [PubMed]
32. Aspect, A.; Dalibard, J.; Roger, G. Experimental Test of Bell's Inequalities Using Time-Varying Analyzers. *Phys. Rev. Lett.* **1982**, *49*, 1804–1807. [CrossRef]
33. Weihs, G.; Jennewein, T.; Simon, C.; Weinfurter, H.; Zeilinger, A. Violation of Bell's inequality under strict Einstein locality conditions. *Phys. Rev. Lett.* **1998**, *81*, 5039–5043. [CrossRef]
34. Maudlin, T. Three measurement problems. *Topoi* **1995**, *14*, 7–15. [CrossRef]
35. Maudlin, T. Space-Time in the Quantum World. In *Bohmian Mechanics and Quantum Theory: An Appraisal*; Cushing, J., Fine, A., Goldstein, S., Eds.; Kluwer: Dordrecht, The Netherlands, 1996; pp. 285–307.
36. Redhead, M. Nonfactorizability, Stochastic Causality, and Passion at a Distance. In *Philosophical Consequences of Quantum Theory: Rejections on Bell's Theorem*; Cushing, J., McMullin, E., Eds.; University of Notre Dame Press: Notre Dame, IN, USA, 1989; pp. 145–153.

37. Shimony, A. Events and Processes in the Quantum World. In *Quantum Concepts in Space and Time*; Penrose, R., Isham, C., Eds.; Oxford University Press: Oxford, UK, 1986; pp. 182–203.
38. Shimony, A. An Exposition of Bell's Theorem. In *Sixty-two Years of Uncertainty: Historical, Philosophical, and Physical Inquiries into the Foundations of Quantum Mechanics*; Miller, A., Ed.; Plenum Press: New York, NY, USA, 1990; pp. 33–43.
39. Dirac, P.A.M. Is there an Æther? *Nature* **1951**, *168*, 906–907. [CrossRef]
40. Dirac, P.A.M. Is there an Æther? *Nature* **1952**, *169*, 702. [CrossRef]
41. Sinha, K.P.; Sivaram, C.; Sudarshan, E.C.G. The superfluid vacuum state, time-varying cosmological constant, and nonsingular cosmological models. *Found. Phys.* **1976**, *6*, 717–726. [CrossRef]
42. Sinha, K.P.; Sivaram, C.; Sudarshan, E.C.G. Aether as a superfluid state of particle-antiparticle pairs. *Found. Phys.* **1976**, *6*, 65–70. [CrossRef]
43. Sinha, K.P.; Sudarshan, E.C.G. The superfluid as a source of all interactions. *Found. Phys.* **1978**, *8*, 823–831. [CrossRef]
44. Volovik. *G.E. The Universe in a Helium Droplet*; Oxford University Press: Oxford, UK, 2003.
45. Huang, K. *A Superfluid Universe*; World Scientific: Singapore, 2017.
46. Albert, D.Z. Special Relativity as an Open Question. In *Relativistic Quantum Measurement and Decoherence*; Breuer, H.-P., Petruccione, F., Eds.; Springer: Berlin/Heidelberg, Germany, 2000.
47. Friedman, M. *Foundations of Space-Time Theories: Relativistic Physics and Philosophy of Science*; Princeton University Press: Princeton, NJ, USA, 1983.
48. Jansen, M. Reconsidering a Scientific Revolution: The Case of Einstein Versus Lorentz. *Phys. Perspect.* **2002**, *4*, 421–446. [CrossRef]
49. Fleming, G.N. *Lorentz Invariant State Reduction, and Localization*; Fine, A., Forbes, M., Eds.; Philosophy of Science Association: East Lansing, MI, USA, 1989; Volume 1988, pp. 112–126.
50. Dorato, M. On Becoming, Relativity, and Nonseparability. *Philos. Sci.* **1996**, *63*, 585–604. [CrossRef]
51. Everett, H. "Relative State" Formulation of Quantum Mechanics. *Rev. Mod. Phys.* **1957**, *29*, 454–462. [CrossRef]
52. Osnaghi, S.; Freitas, F.; Olival, F. The Origin of the Everettian Heresy. *Stud. Hist. Philos. Mod. Phys.* **2009**, *40*, 97–123. [CrossRef]
53. Barrett, J.A.; Byrne, P. (Eds.) *The Everett Interpretation of Quantum Mechanics: Collected Works 1955–1980 with Commentary*; Princeton University Press: Princeton, NJ, USA, 2012.
54. Ghirardi, G.C.; Pearle, P. *Elements of Physical Reality, Nonlocality and Stochasticity in Relativistic Dynamical Re-Duction Models*; Fine, A., Forbes, M., Wessels, L., Eds.; Philosophy of Science Association: East Lansing, MI, USA, 1991; Volume 2, pp. 35–47.
55. Ghirardi, G.; Grassi, R. Outcome predictions and property attribution: The EPR argument reconsidered. *Stud. Hist. Philos. Sci. Part A* **1994**, *25*, 397–423. [CrossRef]
56. Pearle, P.; Ring, J.; Collar, J.I.; Iii, F.T.A. The CSL Collapse Model and Spontaneous Radiation: An Update. *Found. Phys.* **1999**, *29*, 465–480. [CrossRef]
57. Maxwell, N. Are Probabilism and Special Relativity Incompatible? *Philos. Sci.* **1985**, *52*, 23–43. [CrossRef]
58. Tittel, W.; Brendel, J.; Gisin, B.; Herzog, T.; Zbinden, H.; Gisin, N. Experimental demonstration of quantum-correlations over more than 10 kilometers. *Phys. Rev. A* **1998**, *57*, 3229–3232. [CrossRef]
59. Howard, D. Einstein on Locality and Separability. *Stud. Hist. Philos. Sci.* **1985**, *16*, 171–201. [CrossRef]
60. Howard, D. Holism, Separability, and the Metaphysical Implications of the Bell Experiments. In *Philosophical Consequences of Quantum Theory: Reflections on Bell's Theorem*; Cushing, J.T., McMullin, E., Eds.; University of Notre Dame Press: Notre Dame, IN, USA, 1989; pp. 224–253.
61. Dowe, P. Wesley Salmon's Process Theory of Causality and the Conserved Quantity Theory. *Philos. Sci.* **1992**, *59*, 195–216. [CrossRef]
62. Dowe, P. Causality and Conserved Quantities: A Reply to Salmon. *Philos. Sci.* **1995**, *62*, 321–333. [CrossRef]
63. Salmon, W. *Causality and Explanation*; Oxford University Press: Oxford, UK, 1998.
64. Kraus, K. *States, Effects, and Operators: Fundamental Notions of Quantum Theory*; Springer: Berlin/Heidelberg, Germany, 1983.
65. Fleming, G.N.; Butterfield, J. Strange Positions. In *From Physics to Philosophy*; Butterfield, J., Pagonis, C., Eds.; Cambridge University Press: Cambridge, UK, 2000; pp. 108–165.
66. Tomonaga, S. On a Relativistically Invariant Formulation of the Quantum Theory of Wave Fields*. *Prog. Theor. Phys.* **1946**, *1*, 27–42. [CrossRef]
67. Schwinger, J. Quantum Electrodynamics I. A Covariant Formulation. *Phys. Rev.* **1948**, *74*, 1439–1461. [CrossRef]
68. Schweber, S.S. *An Introduction to Relativistic Quantum Field Theory*; Row, Peterson & Co.: Evanston, IL, USA, 1961.
69. Aharonov, Y.; Albert, D.Z. Is the usual notion of time evolution adequate for quantum-mechanical systems? II. Relativistic considerations. *Phys. Rev. D* **1984**, *29*, 228–234. [CrossRef]
70. Fleming, G.N. On a Lorentz Invariant Quantum Theory of Measurement. *Ann. N. Y. Acad. Sci.* **1986**, *480*, 574–575. [CrossRef]
71. Fleming, G.N. Just How Radical is Hyperplane Dependence? In *Perspectives on Quantum Reality: Non-Relativistic, Relativistic, and Field-Theoretic*; Clifton, R., Ed.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1996; pp. 11–28.
72. Eberhard, P.H. Bell's theorem and the different concepts of locality. *Il Nuovo C. B* **1978**, *46*, 392–419. [CrossRef]
73. Shanks, N. Probabilistic Physics and the Metaphysics of Time. *S. Afr. J. Philos.* **1991**, *10*, 37–43.
74. Lewis, D. Humean Supervenience Debugged. *Mind* **1994**, *103*, 473–490. [CrossRef]
75. Sobel, J.H. *Puzzles for the Will*; University of Toronto Press: Toronto, ON, Canada, 1998.
76. Popper, K.R. The Propensity Interpretation of Probability. *Br. J. Philos. Sci.* **1959**, *10*, 25–42. [CrossRef]

77. Popper, K.R. Quantum Mechanics without the Observer. In *Quantum Theory and Reality*; Bunge, M., Ed.; Springer: Berlin/Heidelberg, Germany, 1967; pp. 7–44.
78. Milne, P. A Note on Popper, Propensities, and the Two-slit Experiment. *Br. J. Philos. Sci.* **1985**, *36*, 66–70. [CrossRef]
79. Ballentine, L.E. Propensity, Probability, and Quantum Theory. *Found. Phys.* **2016**, *46*, 973–1005. [CrossRef]
80. Brukner, Č. On the Quantum Measurement Problem. In *Quantum [Un]Speakables II The Frontiers Collection*; Bertlmann, R., Zeilinger, A., Eds.; Springer: Berlin/Heidelberg, Germany, 2017; pp. 95–117.
81. Lewis, D. A Subjectivist's Guide to Objective Chance. In *Studies in Inductive Logic and Probability*; Jeffrey, R.C., Ed.; University of California Press: Los Angeles, CA, USA, 1980; Volume II, pp. 263–293.
82. Suárez, M. Quantum propensities. *Stud. Hist. Philos. Mod. Phys.* **2007**, *38B*, 418–438. [CrossRef]
83. Suárez, M. A critique of empiricist propensity theories. *Eur. J. Philos. Sci.* **2014**, *4*, 215–231. [CrossRef]
84. Peacock, K.A.; Maudlin, T. Quantum Non-Locality and Relativity: Metaphysical Intimations of Modern Physics. *Philos. Rev.* **1994**, *105*, 259. [CrossRef]
85. Ney, A.; Albert, D.A. (Eds.) *The Wave Function. Essays on the Metaphysics of Quantum Mechanics*; Oxford University Press: New York, NY, USA, 2013.
86. Egg, M.; Esfeld, M. Primitive ontology and quantum state in the GRW matter density theory. *Synthese* **2015**, *192*, 3229–3245. [CrossRef]
87. Von Neumann, J. *Mathematische Grundlagen der Quantenmechanik*; Springer: Berlin/Heidelberg, Germany, 1932.
88. Omnes, R. *Quantum Philosophy. Understanding and Interpreting Contemporary Science*; Princeton University Press: Princeton, NJ, USA, 1999.
89. Bricmont, J. *Making Sense of Quantum Mechanics*; Springer Science and Business Media LLC: Dordrecht, The Netherlands, 2016.
90. McCall, S. QM and STR: The Combining of Quantum Mechanics and Relativity Theory. *Philos. Sci.* **2000**, *67*, S535–S548. [CrossRef]
91. Myrvold, W.C. On peaceful coexistence: Is the collapse postulate incompatible with relativity? *Stud. Hist. Philos. Mod. Phys.* **2002**, *33*, 435–466. [CrossRef]
92. Maudlin, T. *Philosophy of Physics. Space and Time*; Princeton University Press: Princeton, NJ, USA, 2012.
93. Lombardi, O.; Fortin, S.; López, C.; Holik, F. (Eds.) *Quantum Worlds. Perspectives on the Ontology of Quantum Mechanics*; Cambridge University Press: New York, NY, USA, 2019.
94. Boge, F.J. *Quantum Mechanics between Ontology and Epistemology*; Springer Science and Business Media LLC: Dordrecht, The Netherlands, 2018; ISBN 9783030107062.
95. Gao, S. The Meaning of the Wave Function. In *Search of the Ontology of Quantum Mechanics*; Cambridge University Press: New York, NY, USA, 2017.
96. Gao, S. *Collapse of the Wave Function: Models, Ontology, Origin, and Implications*; Cambridge University Press: New York, NY, USA, 2018.