Quantum Nonlocality Explained

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Abstract

Quantum theory's violation of remote outcome independence is assessed in the context of a novel interpretation of the theory, in which the unavoidable distinction between the classical and quantum domains is understood as a distinction between the manifested world and its manifestation.

1 Preliminaries

There are at least nine formulations of quantum mechanics [1], among them Heisenberg's matrix formulation, Schrödinger's wave-function formulation, Feynman's path-integral formulation, Wigner's phase-space formulation, and the density-matrix formulation. The idiosyncracies of these formations have much in common with the inertial reference frames of relativistic physics: anything that is not invariant under Lorentz transformations is a feature of whichever *language* we use to describe the physical world rather than an *objective feature* of the physical world. By the same token, anything that depends on the particular formulation of quantum mechanics is a feature of whichever mathematical tool we use to calculate the values of observables or the probabilities of measurement outcomes rather than an objective feature of the physical world.

That said, when it comes to addressing specific questions, some formulations are obviously more suitable than others. As Styer *et al.* [1] wrote,

> The ever-popular *wavefunction formulation* is standard for problem solving, but leaves the conceptual misimpression that [the] wavefunction is a physical entity rather than a mathematical tool. The *path integral formulation* is physically appealing and

> generalizes readily beyond the domain of nonrelativistic quantum mechanics, but is laborious in most standard applications.

When it comes to the problem of interpretation, of making physical sense of the theory, of giving some account of the nature of the physical world and/or our epistemological relation to it that serves to explain how it is that the statistical regularities predicted by the theory come out the way they do, or the problem of establishing the theory's semantic consistency, Feynman's path-integral formulation [2] far surpasses the wave-function formulation.

The term "semantic consistency" was introduced by von Weizsäcker. By the semantic consistency of a theory he meant "that its preconceptions, how we interpret the mathematical structure physically, will themselves obey the laws of the theory" [3, p. 260]. In the context of the wave-function formulation, the challenge of establishing the semantic consistency of quantum mechanics is formidable. What needs to be shown is that the correlations predicted by the theory are consistent with the existence of their correlata. While the existence of measurement outcomes is presupposed by the theory and for this reason cannot be accounted for by it, it obviously has to be consistent with it, and this does not seem to be the case. The stumbling block is the so-called eigenvalue-eigenstate link, which postulates that probability 1 is sufficient for factuality. Here is how this interpretive principle was formulated by Dirac [4, pp. 46–47]:

> The expression that an observable "has a particular value" for a particular state is permissible . . . in the special case when a measurement of the observable is certain to lead to the particular value, so that the state is an eigenstate of the observable.

The wave-function formulation presents us not only with the challenge to explain why the unitary evolution is disrupted by the occasional collapse, which only results in the assignment of probability 1 to a particular outcome, but also with the challenge to explain the factuality of that outcome [5]. That this cannot be done is the gist of insolubility proofs of the so-called objectification problem due to Mittelstaedt [6, Sect. 4.3b] and Busch *et al.* [7, Sect. III.6.2]. If one tries to turn this problem into a postulate by adopting the eigenvalue–eigenstate link, inconsistency results, as was pointed out by Bub [8]:

> The basic question is whether it is consistent with the unitary dynamics to take the macroscopic measurement "pointer" or, in general, the macroworld as definite. The answer is "no," if we

> accept an interpretative principle sometimes referred to as the "eigenvalue-eigenstate link."[1]

Since we have no reason to doubt either the validity of the correlations that quantum mechanics predicts or the existence of their correlata, it must be possible to demonstrate the consistency of the correlations with their correlata, but for this one has to relinquish the eigenvalue–eigenstate link. The demonstration then proceeds in two steps. The first step is to show that the physical world cannot be spatially differentiated (or partitioned) "all the way down." The spatial differentiation of the physical world cannot be complete. If conceptually we keep dividing space into smaller and smaller regions, we reach a point beyond which the distinctions between regions we make in our minds cease to exist, or cease to correspond to anything in the actual physical world. Hence, physical space cannot be modeled as an actually existing manifold of intrinsically distinct points. This invalidates the insolubility proofs of the objectification problem, inasmuch as these implicitly assume that the spatial differentiation of the physical world is complete.

But if physical space cannot be modeled as an actually existing manifold of points labeled by triplets of real numbers, then physical time cannot be represented by an actually existing set of instants labeled by real numbers, and this means that the wave function's dependence on time cannot be the continuous time-dependence of an evolving physical state. The t in $\psi(t)$ can only refer to the time of the measurement to the possible outcomes of which $\psi(t)$ serves to assign probabilities. Bohr was right: what happens between a system preparation and a measurement is a holistic phenomenon, which cannot be decomposed into the unitary evolution of a quantum state and a subsequent "collapse" of the same:

> all unambiguous interpretation of the quantum mechanical formalism involves the fixation of the external conditions, defining the initial state of the atomic system concerned and the character of the possible predictions as regards subsequent observable

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[1] Bub claims that the unitary "dynamics" can be made consistent with the existence of measurement outcomes by stipulating that "the decoherence 'pointer' selected by environmental decoherence" is always definite. Decoherence then "guarantees the continued definiteness or persistent objectivity of the macroworld." Decoherence, however, merely displaces the coherence of the system composed of apparatus and object system into the degrees of freedom of the environment, causing the objectification problem to reappear as a statement about the system composed of environment, apparatus, and object system. Since the mixture obtained by tracing out the environment does not admit an ignorance interpretation, it can resolve the problem only FAPP (Bell's universally adopted abbreviation of "for all practical purposes").

> properties of that system. Any measurement in quantum theory can in fact only refer either to a fixation of the initial state or to the test of such predictions, and it is first the combination of measurements of both kinds which constitutes a well-defined phenomenon. [9]

This renders the wave-function formulation unsuitable for addressing the problem of interpretation.

The second step of the demonstration of the semantic consistency of quantum mechanics is to deduce from the incompleteness of the spatiotemporal differentiation of the physical world the existence of a non-empty class of objects whose positions are "smeared out" only relative to an imaginary spatiotemporal background that is more differentiated than the physical world. If anything truly deserves the label "macroscopic," it is these objects. Here are the two steps in outline (for detailed arguments see Refs. [5, 10, 11, 12, 13]):

Step 1. While quantum mechanics can tell us that the probability of finding a particle in a *given* region of space is 1, it is incapable of *giving* us a region of space. For this a detector is needed. A detector is needed not only to indicate the presence of a particle in a region but also—and in the first place—to physically realize a region, so as to make it possible to attribute to a particle the property of being inside. Speaking more generally, a macroscopic apparatus is needed not only to indicate the possession of a property by a quantum system but also—and in the first place—to make a set of properties available for attribution to the system.[2] (In addition a macroscopic clock is needed to realize attributable times.) But if detectors are needed to realize regions of space, space cannot be intrinsically partitioned. If at all we conceive of it as partitioned, we can do so only as far as regions of space can be realized—i.e., to the extent that the requisite detectors are physically realizable. Because this extent is limited by the indeterminacy principle, the spatial differentiation of the physical world is incomplete; it does not go "all the way down."

Step 2. In an incompletely differentiated world, there will be objects whose position distributions are and remain so narrow that there are no detectors with narrower position distributions. Since the positions of these objects are indefinite only relative to an imaginary spatiotemporal background that is more differentiated than the actual physical world, these are

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[2] This of course is vintage Bohr: the "procedure of measurement has an essential influence on the conditions on which the very definition of the physical quantities in question rests" [14].

the objects that truly deserve the label "macroscopic." While decoherence arguments can solve the objectification problem only FAPP, they quantitatively support the existence of macroscopic objects, the indefiniteness of whose positions is never revealed in the only way it could be revealed, i.e., through a departure from what the classical laws predict. The testable correlations between the outcomes of measurements of macroscopic positions are therefore consistent with *both* the classical *and* the quantum laws. This makes it possible to attribute to macroscopic positions a measurement-independent reality, and that makes it possible for macroscopic positions to define the obtainable values of observables and to indicate the outcomes of measurements.

2 Beyond semantic consistency

Trigger terms like "measurement apparatus," "macroscopic object," and "Bohr" are likely to elicit charges of instrumentalism, Copenhagenism, or some such. Common or garden instrumentalism, however, leaves the meaning of "macroscopic" up for grabs. What has been accomplished so far is a consistent definition of "macroscopic" in the theory's own terms. That ought to count for something, but it is only the beginning, a part of the preliminaries.

To be able to go beyond establishing semantic consistency, to give some account of the nature of the physical world and/or our epistemological relation to it that serves to explain how it is that the statistical regularities predicted by the theory come out the way they do, we need to replace the untenable eigenvalue–eigenstate link by a different interpretive principle, and we need a different formulation of the theory to do this, namely Feynman's [2].

Both the wave-function formulation and Feynman's feature a pair of dynamical principles. In the former they are unitary evolution and collapse, in the latter they are summation over amplitudes (followed by taking the absolute square of the sum) and summation over probabilities (preceded by taking the absolute square of each amplitude). In the context of the wave-function formulation, unitary evolution seems "normal"; what calls for explanation is collapse. In the context of Feynman's formulation, adding probabilities seems "normal" as it is what classical probability theory leads us to expect; what calls for explanation is why we have to add amplitudes. What is at issue, therefore, is not what causes the wave function to collapse but why we have to add amplitudes whenever quantum mechanics requires us to do so. To answer this question I have proposed the following interpretive principle [5, 12, 13]:

(I) Whenever quantum mechanics requires us to add amplitudes, the distinctions we make between the alternatives correspond to nothing in the physical world.

This is a statement about the structure or constitution of the physical world, not a statement merely of our practical or conceptual limitations.

While the wave-function formulation stumps us with the dual problem of collapse and objectification, Feynman's formulation presents us with a question to which there is a straightforward answer. The reason why quantum mechanics requires us to add amplitudes is that the distinctions we make between the alternatives cannot be objectified (represented as real).

Armed with a new interpretive principle, we set out to apply it to two paradigmatic setups, one concerning distinctions between *regions of space*, the other concerning distinctions between *things*. Applied to a two-way interferometer experiment, (I) tells us that the distinction we make between "the particle went through the left arm" and "the particle went through the right arm" corresponds to nothing in the physical world. Since this distinction rests on *spatial* differences between the alternatives, it follows that space cannot be an intrinsically differentiated expanse. Its so-called parts need to be physically realized by the sensitive regions of detectors (defined in terms of macroscopic positions), and we have seen that the indeterminacy principle prevents them from being realized "all the way down."

Applied to an elastic scattering event involving two particles of the same type (say, two incoming particles N and S, two outgoing particles E and W), (I) tells us that the distinction we make between the alternative identifications

$$N = E, S = W \quad \text{or} \quad N = W, S = E$$

corresponds to nothing in the physical world. There is no answer to the question: "Which outgoing particle is identical with which incoming particle?" Now why would that be? Here, too, there is a straightforward answer: because the incoming particles (and therefore the outgoing ones as well) are *one and the same entity*. What's more, there is no compelling reason to believe that this identity ceases when it ceases to have observable consequences owing to the presence of individuating properties. We are free to take the view that *intrinsically* each particle is numerically identical with every other particle. What presents itself here and now with these properties and what presents itself there and then with those properties is one and the same entity.[3] In what follows I shall call it "Being." If you prefer any other name, be my guest.

The following brief reflection leads to much the same conclusion. While the non-relativistic theory allows us to conceive of a physical system as being composed of a definite number of parts, the relativistic theory requires us to treat the number of a system's parts as just another quantum observable (which, as will be explained in the following section, has a definite value only if and when it is measured). There is therefore a clear sense in which a quantum system is always one, the number of its parts being just one of its properties.

3 Manifestation

Perhaps the main reason it is so hard to make sense of the quantum theory is that it answers a question we are not in the habit of asking. Instead of asking what the ultimate constituents of matter are and how they interact and combine, we should ask: *how are forms manifested?* This question, too, has a straightforward answer [5, 12]: *The shapes of things are brought into being with the help of reflexive spatial relations.* By entering into reflexive spatial relations, Being gives rise to (i) what looks like a multiplicity of relata if the reflexive quality of the relations is ignored and (ii) what looks like a substantial expanse if the spatial quality of the relations is reified. Because the relations are reflexive, the multiplicity of the relata is apparent rather than real,[4] and because physical space, insofar as it consists of anything, consists of spatial relations, the spatial quality belongs to the relations; they do not owe it to a substantial expanse. But if physical space is the set of all reflexive relations, the shapes of things are subsets of this set; they are particular sets of spatial relations.

The view put forward here goes farther in relationism—the doctrine that space and time are a family of spatial and temporal relations holding among the material constituents of the universe—in that it also affirms that the ultimate material constituents are formless. While fundamental

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[3] According to French [15], quantum mechanics is "compatible with two distinct metaphysical 'packages,' one in which the particles are regarded as individuals and one in which they are not." Esfeld [16] begs to differ: it is not "a serious option to regard quantum objects as possessing a primitive thisness (haecceity) so that permuting these objects amounts to a real difference."

[4] Does this mean that the material world is unreal, as some illusionistic philosophies assert? By not means, for the material world owes its existence to a multitude of reflexive relations as well as to an intrinsically undifferentiated Being, and this multitude is real.

particles are routinely described as pointlike, what is meant is that they lack internal structure. Lack of internal structure can be inferred from the scale-invariance of a particle's effective cross-section(s) in scattering experiments with probe particles that are themselves pointlike in this sense, but only down to the de Broglie wavelength of the probe particles. There can therefore be no evidence of complete absence of internal structure, let alone evidence of a literally pointlike form. For further reasons why fundamental particles ought to be conceived as formless see Ref. [12, Sect. 9]. Conceived accordingly, the shapes of things resolve themselves into sets of spatial relations between *formless* relata, which are numerically identical, i.e., identically the same Being. The truism that the universe lacks a position because it lacks *external* spatial relations thus has a fitting complement: a fundamental particle lacks a form because it lacks *internal* spatial relations.

To my mind, the most fruitful way to understand the indispensable distinction between the classical or macroscopic domain (containing measurement-independent properties) and the non-classical or quantum domain (whose properties exist only if and when they are measured) is that it is essentially a distinction between the *manifested world* and its *manifestation.*

Three questions may arise at this point. Is the distinction between the two domains truly indispensable? Is it true that the properties of the quantum domain only exist if and when they are measured? And how on Earth are we to conceive of the manifestation of the macroworld—the process by which Being enters into reflexive spatial relations?

Much effort has been and continues to be directed towards reducing one domain to the other,[5] by showing how the classical domain emerges from the quantum domain. Recent attempts to understand "the quantum origins of the classical" [17], "the appearance of a classical world in quantum theory" [18], or "the quantum-to-classical transition" [19] capitalize on decoherence. Decoherence, however, being a quantum-mechanical phenomenon confined to the unitary propagation of correlations, has no bearing on the existence of the correlata. Unitary dynamics, as the insolubility proofs of the objectification problem have shown, cannot account for the existence of a

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[5] According to an anonymous referee of a different paper, to solve the quantum measurement problem "means to design an interpretation in which measurement processes are not different in principle from ordinary physical interactions." Since quantum mechanics describes interactions in terms of correlations between the possible outcomes of measurements performed on the interacting systems, one is left to wonder what the referee could have meant by an "ordinary physical interaction."

domain in which measurements have outcomes.[6] In reality, neither domain can be dispensed with. What happens in the quantum domain can only be described in terms of correlations between measurement outcomes. To describe measurements and their outcomes we need the language of interacting objects and causally connected events, and this "classical" language is applicable only to the classical domain [20]. Paraphrasing Kant's famous statement that "Thoughts without content are empty, intuitions without concepts are blind" [21, p. 193], we may say that without measurements the formal apparatus of quantum mechanics is empty, while measurements without the formal apparatus of quantum mechanics are blind. Together, measurements and the formal apparatus afford us glimpses of what lies beneath, behind, or beyond the classical domain. As Falkenburg has stressed in her book *Particle Metaphysics* [22], a wholesome antidote to mathematical literalism,

> to our present knowledge subatomic reality is not a micro-world on its own but a part of empirical reality that exists relative to the macroscopic world, in given experimental arrangements and well-defined physical contexts outside the laboratory.... The opposite bottom-up explanation of the classical macroscopic world in terms of electrons, light quanta, quarks, and some other particles remains an empty promise. (pp. 339–340)

If this does not answer the second question as well, the 3-particle *gedanken* experiment discussed by Greenberger, Horne, and Zeilinger [23] may be invoked. Three spin-1/2 particles are prepared in such a way that whenever the three spins are measured with respect to the x axis, the product of the outcomes, in suitable units, will be -1, and whenever one spin is measured with respect to the x axis and the two other spins are measured with respect to the y axis, the product of the outcomes will be $+1$. If these measurements revealed properties x_i and y_i $(i = 1, 2, 3)$ that the particles did possess before the measurements were made—properties they would also possess if the measurements were not made—then it would be possible to satisfy these four equations:

$$x_1\,y_2\,y_3 = 1, \quad y_1\,x_2\,y_3 = 1, \quad y_1\,y_2\,x_3 = 1, \quad x_1\,x_2\,x_3 = -1. \tag{1}$$

Since the product of the left-hand sides of the first three equations is equal to $x_1\,x_2\,x_3$ while the product of the right-hand sides of these equations

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[6] See also Note 1.

equals $+1$, the last equation cannot be satisfied if the first three are satisfied. The assumption that the measurements merely reveal properties that already existed before the measurements were made thus leads to a contradiction, and therefore is wrong. These measurements do not reveal properties that the particles would also possess if no measurements had been made. The measured spin components are *created* by being measured. They only exist *if* they are measured.

What was claimed was that the properties of the quantum domain only exist if and when they are measured. What about the "when" part? Consider a spin-1/2 particle, and suppose that we measure its spin twice, once at the time t_1 with respect to an axis A_1 and again at the time t_2 with respect to an axis A_2. If the measurement at t_1 yields *up*, we can predict that the measurement at t_2 will yield *up* with probability $\cos^2(\alpha/2)$, where α is the angle between the two axes. But if the measurement at t_2 yields *up*, we can equally *postdict* (on the basis of *this* outcome) that the measurement at t_1 must have yielded *up* with the same probability. To experimentally verify the prediction, we use a preselected ensemble: we select those pairs of measurements that yield *up* at t_1 and measure the relative frequencies with which *up* is obtained at t_2 for different orientations of A_2. To experimentally verify the postdiction, we use a postselected ensemble: we select those pairs of measurements that yield *up* at t_2 and measure the relative frequencies with which *up* is obtained at t_1 for different orientations of A_1. As far as the mathematics is concerned, the situation is time-symmetric.

The story found in most textbooks is not. If both measurements yield *up* with respect to their respective axes, that story goes like this: (i) the particle's spin is *up* with respect to A_1 not only at t_1 but also during the entire interval between t_1 and t_2; (ii) at t_2 it changes from being *up* with respect to A_1 to being *up* with respect to A_2. If this story were actually supported by quantum mechanics, then so would be the following story: (i) the particle's spin is *up* with respect to A_2 not only at t_2 but also during the entire interval between t_1 and t_2; (ii) at t_1 it changes from being *up* with respect to A_1 to being *up* with respect to A_2. According to the first story, the reason why the particle's spin is *up* with respect to A_1 between t_1 and t_2 is that it is found to be *up* with respect to A_1 at t_1. According to the second story, the reason why the particle's spin is *up* with respect to A_2 during the same interval is that it is found to be *up* with respect to A_2 at t_2.

If the second is not a credible story, then neither is the first. If the measurement outcome at t_2 does not cause the particle's spin to have been *up* with respect to A_2, then the measurement outcome at t_1 does not cause the particle's spin to be subsequently *up* with respect to A_1. The particle's spin is *up* only if *and only when* it is found to be *up*. So much for the first two questions.

If the kinematical properties of microscopic objects—their positions, momenta, energies, etc.—only exist if and when they are indicated by the behavior of macroscopic objects, then macroscopic objects cannot be said to be *made of* microscopic ones.[7] Atoms and subatomic particles must in some way be responsible for the existence of the objects that populate the familiar world of everyday experience, but they cannot play the role of interacting constituent parts. Instead, they are instrumental in the manifestation of the (macro)world. This brings us to the third question. What do I mean by the manifestation of the (macro)world? How are we to conceive of it?

To begin with, since the manifestation of the world includes the manifestation of both space and time, we cannot conceive of it as a process that takes place in space and time. We keep looking for the origin of the universe at the beginning of time, but this is an error of perspective. The origin is Being, intrinsically undifferentiated, co-extensive with space and time yet transcendent of spatial and temporal distinctions. The manifestation of the world consists in a transition from the undifferentiated state of Being to a state that allows itself do be described in the classical language of interacting objects and causally related events—a transition from absolute unity to the multiplicity of the manifested world. Quantum theory thus reverses the explanatory arrow of common sense and folk physics (a.k.a. classical physics): instead of trying to explain wholes in terms of interacting parts, it shows how the multiplicity of the world emerges from the unity of Being.

This transition from absolute unity to the multiplicity of the manifested world passes through several stages. Through these stages the world's differentiation into distinguishable objects and distinguishable regions of space is gradually realized. There is a stage at which Being appears to be a multitude of formless particles. This stage is probed by high-energy physics and known to us through correlations between the counterfactual clicks of nonexistent detectors, i.e., in terms of transition probabilities between in-states and out-states. There are stages that mark the emergence of form, albeit a type of form that cannot yet be visualized. The forms of nucleons, nuclei, and atoms can only be mathematically described, as probability distributions over abstract spaces of increasingly higher dimensions. At energies low enough for atoms to be stable, it becomes possible to conceive of objects with

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[7] When physicists reflect on the motives for their research, they nontheless often claim (especially on TV, in press releases, and in grant applications) that their aim is to discover the elementary building blocks of the universe and the processes by which they interact with each other—a thoroughly schizoid state of affairs.

fixed numbers of components, and these we describe in terms of correlations between the possible outcomes of unperformed measurements. The next stage—closest to the actual manifested world—contains the first objects with forms that can be visualized—the atomic configurations of molecules. But it is only the final stage—the manifested macroscopic world—that contains the actual detector clicks and the actual measurement outcomes that have made it possible to discover and study the correlations in terms of which quantum mechanics describes the transition from the unity of Being to the multiplicity of the manifested world.

A further question may arise at this point. Since most measurable quantities only exist, or only have values, if and when they are actually measured, the properties of macroscopic objects cannot be accounted for in terms of the properties of microscopic objects and their interactions. Then what about the manifestation of the macroworld? Can this be understood without reference to the properties of microscopic objects? It can, for atoms are known to us through correlations between measurement outcomes, and subatomic particles are known to us through correlations between detector clicks. As their respective roles in the manifestation of macroscopic objects can be understood in terms of conditional propositions stating correlations, they do not involve properties that only exist if and when they are measured.

Many of the mysteries surrounding quantum mechanics become clear in this new light. Why, after all, is the general theoretical framework of contemporary physics a probability calculus, and why are the probabilities assigned to measurement outcomes? If quantum mechanics concerns a transition through which the differentiation of the world into distinguishable objects and distinguishable regions is gradually realized, the question arises as to how the intermediate stages are to be described—the stages at which the differentiation is incomplete and the distinguishability between objects or regions of space is only partially realized. The answer to this question is that whatever is not completely distinguishable[8] can only be described by assigning probabilities to what is completely distinguishable, namely to the different possible outcomes of a measurement. What is instrumental in the manifestation of the world can only be described in terms of what happens in the manifested world, or else in terms of correlations between events that could happen in the manifested world.

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[8] It is also worth stressing that the indeterminism of quantum mechanics is rooted in this underlying indeterminacy. Instead of consisting *fundamentally* in the existence of unpredictable changes disrupting a predictable evolution, it is a consequence of indeterminacies that *evince* themselves through unpredictable transitions in the values of outcome-indicating positions (Bub's "decoherence pointers").

For readers with an adequate philosophical background it may be of interest to compare the manifestation of the macroworld with the classical philosophical concept of the emergence of the Many from a One. In classical metaphysics, this emergence used to be conceived as running parallel to predication: an immaterial essence or predicable universal becomes instantiated as an impredicable material individual. This instantiation, moreover, was conceived in the framework of a Platonic–Aristotelian dualism, which postulates an instantiating medium (matter and/or space) in or by which the essences or universals get instantiated. The manifestation of the macroworld, by contrast, requires no separate medium and implies no dualism. All that is required is the realization of spatial relations. Being may be said to manifest the macroworld *within* itself—after all, the macroworld is manifested with the help of *reflexive* relations—rather than in something other than itself.

4 The EPR-Bohm scenario

The core principle of Feynman's formulation of quantum mechanics—add amplitudes if nothing "destroys" the interference between the alternatives [2] —covers not only the two-slit experiment with electrons, which according to Feynman [24, Sect. 1–1] "has in it the heart of quantum mechanics," and the "miraculous identity of particles of the same type," which according to Misner *et al.* [25, p. 1215] "must be regarded, not as a triviality, but as a central mystery of physics," but also the entanglement of systems in spacelike relation, which for Schrödinger [26] was "not … one but rather *the* characteristic trait of quantum mechanics." In our elastic scattering experiment with particles of the same type, initially moving northward and southward, respectively, the final probability of finding one particle moving eastward and one moving westward takes the form

$$|\langle EW|NS\rangle \pm \langle WE|NS\rangle|^2, \tag{2}$$

where the sign depends on whether the particles are bosons or fermions. This result can also be obtained by using the Born rule with the following initial and final states:

$$|\psi_i\rangle = \frac{1}{\sqrt{2}}\big(|NS\rangle \pm |SN\rangle\big), \quad |\psi_f\rangle = \frac{1}{\sqrt{2}}\big(|EW\rangle \pm |WE\rangle\big). \tag{3}$$

It is now readily seen why the evolving-states formulation of quantum mechanics requires the use of (anti)symmetrized particle states. If we were to use $|AB\rangle$ instead of the (anti)symmetrized product, we would introduce, in addition to the physically warranted distinction between "the particle in A" and "the particle in B," the physically unwarranted distinction between the "first" or "left" particle and the "second" or "right" particle (in the expression $|AB\rangle$). This would be justified if the particles carried "identity tags" corresponding to "left" and "right," in which case we would be required to add probabilities, not amplitudes. If the distinction between "the particle in A" and "the particle in B" is the only physically warranted distinction, the distinction between the "left" particle and the "right" particle must be eliminated, and this is achieved by (anti)symmetrization.

To apply the core principle of Feynman's formulation to a pair of entangled systems in spacelike relation, we need to take account of the fact that Born probabilities are time-symmetric. The Born rule can be used to assign probabilities to the possible outcomes of an earlier measurement on the basis of the actual outcome of a later measurement as well as vice versa. (This is one more reason why quantum states should not be thought of as evolving states.) Let us begin with a more formal outline of Feynman's formulation ([10, Sect. 11] or [13, Sect. 5.1]):

Premise 1. Quantum mechanics provides us with algorithms for assigning probabilities to possible measurement outcomes on the basis of actual outcomes. Probabilities are calculated by summing over alternatives. Alternatives are possible sequences of measurement outcomes.[9] Associated with each alternative is a complex number called "amplitude."

Premise 2. To calculate the probability of a particular outcome of a measurement M_2, given the actual outcome of a measurement M_1, choose a sequence of intermediate measurements, and apply the appropriate rule.

Rule C. If the intermediate measurements are made (or if it the setup makes it possible to infer from other measurements what their outcomes would have been if they had been made), first square the absolute values of the amplitudes associated with the alternatives and then add the results.

Rule Q. If the intermediate measurements are not made (and if the setup does not make it possible to infer from other measurements what their

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[9] It deserves to be stressed that alternatives are defined in terms of measurement outcomes. The only referents needed to formulate the laws of quantum mechanics are property-indicating events.

> outcomes would have been), first add the amplitudes associated with the alternatives and then square the absolute value of the result.[10]

Because Born probabilities are time-symmetric, the intermediate measurements need not be intermediate *in time.* In an EPR-Bohm setup [29, pp. 614–622], M_1 might be a spin measurement on particle 1 with respect to axis A, M_2 might be a spin measurement on particle 2 with respect to axis B, and the intermediate measurement might be a spin measurement on particle 1 with respect to any axis, which could have been made (but was not) right after the time of the molecule's dissociation into two particles of spin 1/2. Adding the two amplitudes and taking the absolute square of the result yields the conditional probability $p(b|a)$:

$$\big|\langle b|u\rangle\langle d|a\rangle^* - \langle b|d\rangle\langle u|a\rangle^*\big|^2 = \big|\langle b|u\rangle\langle a|d\rangle - \langle b|d\rangle\langle a|u\rangle\big|^2. \tag{4}$$

The left-hand side reflects the logical order (as usual, from right to left): the ket $|a\rangle$ ("up" with respect to axis a) represents the outcome on the basis of which the probability $p(b|a)$ is assigned, the ket $|b\rangle$ ("up" with respect to axis b) represents the outcome to which the probability $p(b|a)$ is assigned, and the kets $|u\rangle$ and $|d\rangle$ represent the possible outcomes of the (logically) intermediate measurement on particle 1, which is not actually made. If this measurement were to yield u, then particle 2 would start out "in" the state $|d\rangle$, and if it were to yield d, then particle 2 would start out "in" the state $|u\rangle$. The negative sign appears because the two amplitudes differ by an exchange of fermions. The complex conjugate amplitudes are used where the logical order is the reverse of the temporal order, which is restored on the right-hand side. If we simplify the right-hand side to

$$p(b|a) = |\langle ba|ud\rangle - \langle ba|du\rangle|^2, \tag{5}$$

the analogy with Eq. (2) becomes obvious. In the evolving-states formulation one obtains the same conditional probability by calculating the joint probability $|\langle ba|S\rangle|^2$, where $|S\rangle$ stands for the singlet state $(|ud\rangle - |du\rangle)/\sqrt{2}$, and dividing it by the marginal probability of finding "up" with respect to axis A. It is worth noting, though, that in order to do the Feynmanesque calculation we do not need to know how to write the singlet state. All we need to know is that the two spins are anti-correlated, as required for the conservation of angular momentum.

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[10] The parenthetical phrases take care of "quantum eraser" setups like that discussed by Englert, Scully, and Walther [27, 28].

Equation (4) is not meant to suggest that some kind of backward causation is involved. The view put forth here is, rather, that no kind of *spatiotemporal* causation is involved—neither forward nor backward nor sideways.

5 Quantum nonlocality

> *For those interested in the fundamental structure of the physical world, the experimental verification of violations of Bell's inequality constitutes the most significant event of the past half-century. In some way our basic picture of space, time, and physical reality must change. These results, and the mysteries they engender, should be the common property of all who contemplate with wonder the universe we inhabit.* — Tim Maudlin [30, p. 4]

In his seminal paper of 1964, Bell [31] used the EPR-Bohm scenario to show that the principle of local causes (also called Einstein locality) was incompatible with quantum mechanics—a result that was hailed by Stapp [32] as "the most profound discovery of science." Schrödinger, in his famous "cat" paper [33], observed that "Measurements on separated systems cannot directly influence each other—that would be magic." Bell showed that the magic was real. His conclusion was that

> In a theory in which parameters are added to quantum mechanics to determine the results of individual measurements, without changing the statistical predictions, there must be a mechanism whereby the setting of one measuring device can influence the reading of another instrument, however remote. [31]

The reason Bell examined deterministic theories, in which parameters are added to quantum mechanics, was not that he was averse to indeterminism but that deterministic theories were the only hope for retaining locality, a hope that was dashed by him for good. While in a deterministic theory locality is doomed by Bell's inequality, in an indeterministic theory it is doomed by perfect correlations. No matter whether measurement outcomes are determined by hidden variables or stochastic, there must be a causal connection between the setting of one apparatus and the reading of another. And since this connection can be accounted for neither by a direct causal influence nor by a common cause in the intersection of the past light cones of the measurement events, it must be nonlocal.

The causality associated with the atemporal process of manifestation casts a new light on quantum theory's violation of remote outcome independence, to use Shimony's term [34]. For quantum mechanics presents us with a so far unrecognized kind of causality—unrecognized, I believe, within the scientific literature albeit well-known to metaphysics, inasmuch as the general philosophical pattern of a single world-essence ("Being") manifesting itself as a multiplicity of individual things is found throughout the world.[11] The causality of the process of manifestation must be distinguished from its more familiar temporal cousin, which links states or events across time or spacetime. This latter causality plays no role in the manifestation. Its usefulness being confined to the world drama, which allows itself to be written in terms of interacting objects and causally connected events, it plays no part in setting the stage for the drama.

An atemporal causality does not, of course, involve a temporal sequence, nor does an atemporal process or transition take place in time. Yet there are stages by which the differentiation of the world into distinguishable objects and distinguishable regions is gradually realized. The coexistent stages of this gradual realization (or becoming real) can be placed along a dimension of logical space that is neither temporal nor spatial, and they can be viewed in a logical sequence, as a transition from undifferentiated unity to the multiplicity of the manifested world, via numerically identical particles, non-visualizable atoms, and partly visualizable molecules. We do, in fact, take much the same liberty when we conceive, as we routinely do, of temporal succession as if it were another spatial dimension. If we have the right to visualize time as a dimension of a 4-dimensional expanse, then we also have the right to imagine an atemporal causal arrow and to say that the multiplicity of the world exists *because* of the spatial relations that Being entertains with itself.

I contend that quantum mechanics violates remote outcome independence for the same reason that the manifestation of the world cannot be explained by processes that connect events across spacetime, spacetime being an aspect of the finished product, the manifested world. The atemporal process by which Being enters into reflexive relations and matter and space come into being as a result, is the nonlocal event *par excellence.* Instead of being an event *in* spacetime, the transition by which Being acquires the aspect of a multiplicity of relata as well as the aspect of a substantial ex-

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[11] Some of its representatives in the Western hemisphere are the Neoplatonists, John Scottus Eriugena, and the German idealists. The quintessential Eastern example is the original (pre-illusionist) Vedanta of the Upanishads [35, 36, 37].

panse is, depending on one's point of view, either "outside" of spacetime (i.e., not localized at all) or coextensive with spacetime (i.e., completely delocalized). The atemporal causality of this event supports the folk causality that connects objects across space and events across spacetime, which helps us make sense of the manifested world as well as of the cognate world of classical physics. But this folk causality throws no light on the process of manifestation nor on the quantum correlations that are instrumental in the process.

I also content that the diachronic correlations between events in timelike relation are as mysterious and inexplicable (in terms of folk causality) as the synchronic correlations between events in spacelike relation. While we know how to calculate either kind of correlation, and therefore know how to calculate the probabilities of possible events on the basis of actual events, we know as little of a physical process by which an event here and now contributes to determine the probability of a *later* event *here* as we know of a physical process by which an event here and now contributes to determine the probability of a *distant* event *now*.

A final word in defense of this last contention. Suppose that we perform a series of position measurements, and that each time exactly one detector clicks. In this case we seem to be entitled to infer the existence of a persistent entity, to think of the clicks given off by the detectors as matters of fact about the successive positions of this entity, and to think of the detectors as detectors. But are we justified in saying that the presence of this entity is responsible for the correlations between the detector clicks?

Since positions only exist, or only have values, if and when they are actually measured, the answer is negative. The click is not caused by the presence of an entity in the detector's sensitive region. Rather, the click is the cause of the presence of an entity in the detector's sensitive region [38, 39]. Moreover, what justifies the interpretation of the detector clicks as indicating the existence of a persistent entity, is an inferred conservation law (provided the inference is justified): it is because each time exactly the same number of detectors click (in this case one) that we can behave *as if* the correlations were caused by a single persistent entity. If each time exactly two detectors click, and if no "identity tags" are associated with the clicks, we can still attribute the clicks to a single persistent entity, but not to two separate, re-identifiable entities. We may still imagine that the correlations between earlier and later clicks are mediated by a single persistent entity, but not that they are mediated by two such entities.[12] And while, as previously

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[12] For a more in-depth discussion of these remarks see Ref. [12, Sect. 7].

remarked, the non-relativistic theory allows us to conceive of a physical system as being composed of a definite number of parts, the relativistic theory requires us to treat the number of a system's parts as just another quantum observable, which has a definite value only if and when it is measured. It allows us to imagine that the correlations between detector clicks are mediated by a single persistent entity—namely Being, which supports the apparent multiplicity of entities by entertaining reflexive spatial relations—but not by a multitude of *individual* entities that propagate from click to click. What is responsible for the quantum-mechanical correlations—the diachronic ones as well as the synchronic ones—is the atemporal causality by which Being manifests the world. The correlations themselves, being instrumental in the process of manifestation, cannot be understood in terms of those kinds of causal stories to which the manifested world lends itself.

So has quantum nonlocality been explained, as the title of this paper appeared to promise? If by "explanation" we mean an account in terms of causal relations across time or spacetime, the answer is No. What I have attempted to explain is why no such explanation is possible. The nonlocality implied by Bell's inequality and related no-go theorems is but the most salient symptom of a much deeper and more general nonlocality. It is the nonlocality of that intrinsically undifferentiated Being, one with every fundamental particle, which manifests the world by entering into reflexive spatial relations. It is the nonlocality of the process of manifestation, which yields an apparent locality (i.e., amenability to local explanation) only in its final outcome, the manifested world.

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