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*Article*

# Completing Quantum Mechanics within the Framework of Local Realism

**Guang-Liang Li**

Independent Researcher, Hong Kong, China; glli@eee.hku.hk

## Abstract

The Copenhagen interpretation presumes the legitimacy of quantum superpositions, attaches "the probabilistic nature" to quantum mechanics, brings observers into axioms of the theory, and claims that quantum mechanics is already a complete theory. Einstein disagreed with this interpretation; he argued against the legitimacy of quantum superpositions, worried about observers in the axioms, and considered quantum mechanics incomplete. Inspired by Einstein, Bell and his followers intended to complete quantum mechanics within the framework of local realism. They derived Bell inequalities, tested them by experiments, and proved Bell's theorem to interpret the experimental results. Regrettably, the experimental results are misinterpreted. This article introduces a new principle, the general principle of measurements, and provides its mathematical proof. Based on this principle, quantum mechanics can be completed within the framework of local realism by using disjunction ("or") as the logical relation between orthonormal vectors spanning any given Hilbert space while keeping its general definition unchanged. Probabilistic predictions given by the completed theory and the current theory are exactly the same. Furthermore, by eliminating observers from the axioms and precluding inexplicable collapses of wave-functions, the completed theory alleviates much difficulty in understanding quantum mechanics and is intuitively comprehensible. In conclusion, Einstein's local-realist world-view is correct.

**Keywords:** Einstein-Bohr debate; Copenhagen interpretation of quantum mechanics; quantum measurement problem; local realism; Einstein's separability principle; Bell inequalities; Bell's theorem; quantum correlation; non-locality (nonlocal-interaction)

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## 1. Introduction

In the Einstein-Bohr debate, Einstein disagreed with the Copenhagen interpretation of quantum mechanics, which presumes the legitimacy of quantum superpositions, attaches "the probabilistic nature" to quantum mechanics, brings observers into axioms of the theory, and claims that quantum mechanics is already a complete theory. The legitimacy of quantum superpositions lies at the heart of the quantum measurement problem and is the essence of the Einstein-Bohr debate [1,2]. The measurement problem concerns the measurement of a quantum-mechanically described *single* object. The object can be microscopic or macroscopic. Unlike microscopic objects, a macroscopic object can be measured repeatedly. Both kinks of objects are expressed by quantum superpositions. The following is a brief summary of the Copenhagen interpretation defended by Bohr in the Einstein-Bohr debate.

If the object is microscopic described by a wave-function $\psi = c_1\psi_1 + c_2\psi_2$, where for $i = 1, 2$, $c_i$ are complex numbers and $\psi_i$ are orthonormal vectors, then orthogonality of the superposed vectors is associated with exclusive properties possessed by the object, representing alternative outcomes obtained by measuring it. When nobody looks, the object possesses such properties represented by $\psi_1$ *and* $\psi_2$ *simultaneously*. For instance, if the object is a particle, two of its different energy levels are exclusive properties. Once an observer performs a measurement on the object, $\psi$ collapses abruptly onto $\psi_1$ *or* $\psi_2$ according to the measurement outcome obtained. The outcomes obtained by measurements are inherently probabilistic. The probability of finding the measurement outcome represented by $\psi_i$ is $|c_i|^2$. If the object is macroscopic, the measurement problem has an analogy in popular science: the famous Schrödinger's cat in a box [3]. The object, denoted by $Q$ with two of its macroscopically distinguishable states $Q^+$ and $Q^-$, is a popular analogy to the quantum-mechanical description of Schrödinger's cat [4]. According to the Copenhagen interpretation, the cat is both alive and dead simultaneously with corresponding probabilities if nobody lifts the lid of the box and looks inside.

Einstein disagreed with the Copenhagen interpretation and argued against quantum superpositions used to describe any object in the real world. Regrettably, Einstein's argument has been misunderstood, mainly because the experimental results of testing Bell inequalities are misinterpreted. Bell inequalities and the corresponding experiments have been discussed intensively in the existing literature (for example, see [5–12]). The present study concerns Einstein's argument in the Einstein-Bohr debate and shows why Bell and his followers failed to interpret the experimental results correctly. Einstein was not opposed to the use of probability in quantum mechanics; he was opposed to the so-called "inherently probabilistic nature" attached by the Copenhagen interpretation to quantum mechanics. Based on a new principle introduced in this article, *the general principle of measurements*, Einstein's argument can be better appreciated. The main findings reported are as follows.

Bell's approach is problematic; the *deterministic correlation* between *distant components* of a separable system in Einstein's local-realist description of the world is mistaken for non-locality in the world described by Bell's theorem [5,11]. Quantum mechanics can be completed within the framework of local realism in a way consistent with the definition of a *general* Hilbert space, which is the mathematical setting for quantum mechanics, so the completed quantum theory can provide the same probabilistic predictions of empirical results as those provided by the current theory. By explaining indeterminism in quantum physics and using disjunction ("or") as the logical relation between superposed orthonormal vectors, the completed quantum theory precludes inexplicable collapses of wave-functions, eliminates observers from the axioms of quantum mechanics, and is intuitively comprehensible, thus alleviating much difficulty experienced by many people in understanding the theory in its present form. Among various world views, Einstein's local-realist world view is correct. Relinquishing Einstein's separability principle as suggested in [13] is unnecessary.

## 2. Einstein's Argument

Consider two *spatially separated, individual* microscopic objects. A *correlation* between them always exists. If the condition demanded by Einstein's *separability principle* is satisfied [13], namely, the objects possess their autonomous, real states independent of each other, then they constitute a *separable* system, and the possibility of describing the objects by non-locality will be precluded. For ease of exposition, call such objects *distant components* of the separable system, or simply call them distant components when no confusion will arise if the corresponding system is not mentioned. Non-locality is also referred to as "nonlocal-interaction" ([11], pp. 1886-1887). Were there nonlocal-interaction in the real world, a measurement performed on one of the distant components would change the state of the other component telepathically; all such telepathic changes are excluded by Einstein's separability principle. Einstein illustrated his separability principle with a simple, non-quantum-theoretical example [13]. The following is a slightly different version of Einstein's original illustration (see Table 1 below).

**Table 1.** Non-quantum-theoretical illustration of Einstein's separability principle.

| Box | Color of Ball in Box |
|---|---|
| I | Red |
| II | Blue |

Two colored balls are *spatially separated* in two boxes. A *correlation* exists between the separated balls. For example, if the color of one ball is blue, the color of the other ball must be red. Before a person lifts the lid of a box and looks inside, which box contains the blue (or red) ball is unknown. Will the color of the ball in the box change when its lid is lifted? Of course not. *The colors of the separated* *balls will remain unchanged regardless of whatever happens to either box.* Clearly, the separated balls are *deterministically* correlated. There is no need of using probability here because no randomness appears in the illustration. In Section 10, Einstein's original illustration will be discussed to show a connection between the purported probabilistic nature attached by the Copenhagen interpretation to quantum mechanics and observers appeared in the axioms of the theory rather than deduced from the axioms.

In his debate with Bohr [1,2], Einstein grounded both locality and realism on his separability principle. Thus, in Einstein's local-realist description of the world, measurements performed on either distant component cannot affect the other component according to locality, and values of all variables describing a distant component exist objectively according to realism. The essence of the Einstein-Bohr debate is the legitimacy of quantum superpositions. Einstein disagreed with Born's probabilistic interpretation of wave-functions, which are expressed as quantum superpositions. Born's probabilistic interpretation cannot account for indeterminism in quantum physics, although it can be used to calculate the probabilities correctly. Once a measurement is performed on a quantum-mechanically described object, the corresponding wave-function collapses abruptly. Because the quantum-mechanical description "cannot be reconciled with the idea that physics should represent a reality in time and space, free from spooky actions at a distance" ([14], p.158), Einstein called it "the fundamental dice-game" ([14], p.149). Besides Born's probabilistic interpretation, observers in the axioms of quantum mechanics also disturbed Einstein.

## 3. Local Realism and EPR Argument

According to [13], Einstein himself did not write the EPR paper (i.e., [1]). He neither mentioned the "elements of physical reality" in his standard argument for the incompleteness of quantum mechanics nor considered the well-known EPR argument (as given in [1]) satisfactory; Podolsky wrote the EPR paper. Thus the EPR argument cannot fully reflect Einstein's own views and deeper philosophical assumptions. Nevertheless, because the EPR argument is widely known, it is still necessary to analyze the role played by the assumptions of locality and realism (local realism) underlying the EPR argument in the context of its logical structure.

Needless to say, the purpose of the EPR argument [1] is to question the completeness of quantum mechanics based on local realism and some less important assumption. As stated by EPR [1]: "In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system." In their argument [1], EPR then continued to reveal a contradiction in the conceptual foundations of quantum mechanics: if quantum mechanics in its present form is *assumed* to be a complete theory, then this *assumption*, together with the criterion of reality, leads to a contradiction. But what is the contradiction they revealed?

To answer the above question, let us consider two well-known statements in the EPR argument [1]: "either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) two physical quantities described by two non-commuting operators cannot have simultaneous reality." One of the two statements must be wrong. According EPR [1]: "Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false."

In other words, the negation of (1) implies the negation of (2). By contra-position, the statement "the negation of (1) implies the negation of (2)" is equivalent to the statement "(2) implies (1)", i.e., "two physical quantities described by two non-commuting operators cannot have simultaneous reality" implies "the description of reality given by the wave function in quantum mechanics is not complete." If the two non-commuting operators are the position operator and the momentum operator, then (2) is a consequence of Heisenberg's uncertainty relation. The negation of (2), i.e., the statement "(2) is false", actually implies the statement "Heisenberg's uncertainty relation is false." Thus the negation of (2) further implies the falsity of Heisenberg's uncertainty relation. The negation of (1) is the statement "quantum mechanics is complete."

As shown above, the contradiction in the conceptual foundations of quantum mechanics in its present form is this: the completeness of quantum mechanics implies the falsity of Heisenberg's uncertainty relation, or equivalently, Heisenberg's uncertainty relation, *if* it holds, implies the incompleteness of quantum mechanics. Because the negation of (2) implies the falsity of Heisenberg's uncertainty relation and is the only other alternative *if* the uncertainty relation holds, EPR "are thus forced to conclude that the quantum-mechanical description of physical reality given by wave functions is not complete." However, is it possible for EPR to endorse Heisenberg's uncertainty relation? As can be seen shortly, the answer to this question must be no.

But what forces EPR to reach their conclusion? In other words, what exactly in the EPR argument imply the incompleteness of quantum mechanics? Is it possible for EPR to consider locality or realism responsible for the incompleteness of quantum mechanics? A positive answer to the above question would lead EPR to reject local realism. As we all know, the EPR argument is grounded on local realism and aims to question the completeness of quantum mechanics. It is the belief of EPR that a complete quantum theory within the framework of local realism is possible [1]. Considering locality or realism responsible for the incompleteness of quantum mechanics contradicts EPR's belief. Clearly, rejecting either of these assumptions would appear entirely unacceptable to EPR.

According to quantum mechanics in its present form, *before* any measurement is performed on a particle, its state is described by a wave-function, which is a quantum superposition, such that the commutation relation for the position operator and the momentum operator holds for this wave-function; *after* a measurement is performed on the particle, the wave-function collapses immediately. The EPR argument rests on the existence of a *correlation* between two spatially separated particles ([15] p.225). According to Einstein's separability principle in his own incompleteness argument [13], the particles are *distant components* of a separable system. As distant components of a separable system, the particles always possess their autonomous, real states independent of each other. The collapses of wave-functions triggered by measurements are exactly due to what Einstein called "spooky actions at a distance". Therefore, it is impossible for EPR to endorse Heisenberg's uncertainty relation.

Bohr defended quantum mechanics. He raised issues concerning practical measurements related to the uncertainty relation but did not mention the correlation between the spatially separated particles [2]. Thus the contradiction in the conceptual foundations of quantum mechanics in its present form cannot be explained away.

## 4. Bell's Approach

Inspired by Einstein, Bell and his followers intended to complete quantum mechanics within the framework of local realism [16]. Bell derived the first of Bell inequalities to be tested by experiments [5,8,10,12] and proved Bell's theorem to interpret the experimental results [5]. To his surprise, his theorem shows Einstein to be wrong in the Einstein-Bohr debate [5,11], which is the opposite of what Bell intended [16,17]. Why does Bell's approach lead him to prove the opposite of what he intended? Can quantum mechanics be completed in a way different from Bell's approach? The questions are still open and concern different understandings or interpretations of Bell's theorem [3,4,6,7,10,11,13,18–20], including those disproving or questioning it [7,20].

Consider the following opinions: 1) regarding hidden-variables theories, what Bell's theorem tell us is that for such theories to *reproduce* the *statistical* predictions given by quantum mechanics, they must be either nonlocal or super-deterministic; the essence of Bell's investigation was whether the perfect correlations predicted by quantum mechanics could be explained locally by introducing "hidden variables", and 2) questioning Bell's theorem amounts to suggesting that the quantum-mechanically calculated probability is incorrect.

Such opinions reflect a fact: there are different understandings or interpretations of Bell's theorem as shown in the literature [3,4,6,7,10,11,13,18–20]. But whatever Bell's theorem tell us may have nothing to do with Einstein's local-realist description of the world, and questioning Bell's theorem should not be considered as saying "the quantum-mechanically calculated probability is incorrect." Bell's theorem is questionable, because Bell mistook the *correlation* between *distant components* of a separable system in Einstein's local-realist description of the world for non-locality in the world described by his theorem [5,10,11]. To address the above issues, let us begin with revisiting Bell's approach. The issues will be further addressed later in Section 9.

When deriving Bell inequalities [5,8,10,12] by resorting to a hidden-variables theory [21–23], Bell and his followers merely tried to *reinterpret quantum mechanics while keeping the theory in its present form intact* [17]. Thus *Bell's approach presumes the legitimacy of quantum mechanics in its present form*. Purportedly obtained from the assumptions underlying the EPR argument, Bell inequalities cannot capture the essence of the Einstein-Bohr debate, namely, the legitimacy of quantum superpositions. Einstein never endorsed any hidden-variables theory ([15], p.254). Nevertheless, Bell regarded Einstein as a proponent of hidden variables [5] and maintained his views (see Ref. /23/ in [24] and [25]). Although neither Bell nor Einstein ever mentioned the "elements of physical reality" [13], some physicists, including Bell's followers [10,11], believe that there exists a linkage between hidden variables and the "elements of physical reality". Such a linkage is nonexistent. Unlike Bell, his followers ground their arguments on the nonexistent linkage; they seem to be unaware of Einstein's separability principle, as can be seen from their understanding and interpretation of Bell's theorem [10,11].

Bell inequalities are not results about quantum mechanics. But the world described by Bell's theorem is the world described by quantum mechanics, which differs substantially from Einstein's local-realist world view. In Einstein's local-realist description of the world, the *correlation* between *distant components* of a separable system is due to some interaction occurred *before* the components spatially separated; *after* the separation, there is no longer any interaction between the *distant components*. But the *correlation* still exists, even though the components have spatially separated [1]. Regrettably, the *correlation* between *distant components* of a separable system in Einstein's local-realist description of the world is mistaken for nonlocal-interaction in the world described by Bell's theorem [11]; the confusion has led to serious consequences as shown below.

One of Bell inequalities, the CHSH inequality [12], has been intensively tested by actual experiments with *single* pairs of *correlated* photons using technologies of modern optics [8,10]. According to Bell's theorem, the Einstein-Bohr debate seems to have been resolved "in the way which Einstein would have liked least" [23]. Nowadays people believe that Einstein's local-realist world view conflicts with the experimental results of testing the CHSH inequality [10,11]. However, derived based on the nonexistent linkage between hidden variables and the "elements of physical reality", *the CHSH inequality merely represents an unsuccessful attempt to reinterpret quantum mechanics by reproducing its statistical predictions while presuming the legitimacy of quantum superpositions*. Thus the CHSH inequality cannot capture the essence of the Einstein-Bohr debate, and *the assumptions underlying the EPR argument as well as Einstein's separability principle are all irrelevant to Bell's theorem*.

But why is the *correlation* between *distant components* of a separable system in Einstein's local-realist description of the world mistaken for non-locality in the world descried by Bell's theorem? Before answering this question, it is necessary to introduce a new principle, *the general principle of measurements*, which is proved as a mathematical theorem.

## 5. General Principle of Measurements

Physical quantities are all measured in the real world based on mathematical models of space and time. Thus the corresponding models must be identified first before the new principle is introduced and proved mathematically. The mathematical model of space is the three-dimensional Euclidean space $\mathbb{R}^3$ endowed with the metric given by the usual distance function between two points in space; a point $z \in \mathbb{R}^3$ represents a precise space coordinate. The mathematical model of time is the set of nonnegative real numbers $R_0$ equipped with the metric given by the usual distance function between two nonnegative real numbers; an element $t \in R_0$ is a precise time coordinate.

To prove the general principle of measurements as a mathematical theorem, let us recall a few definitions in "metric space" and "point-set topology". A metric space is denoted by $(X, d)$, where $X$

is a set, and $d$ is a metric on $X$. Let $r > 0$ be a real number. For $x \in X$, the open ball with center $x$ and radius $r$ is

$$B(x;r) = \{y \in X : d(x,y) < r\}. \tag{1}$$

Any open subset of $X$ is a union of open balls. All open subsets of $X$ constitute a metric topology $\mathcal{T}_X$ for $X$. The metric topology $\mathcal{T}_X$ and $X$ form a metric topological space. Consider $x \in S$ where $S \in \mathcal{T}_X$. If there exists $r > 0$ such that

$$B(x;r) \cap S = \{x\}, \tag{2}$$

then $x$ is an isolated point of $S$. Denote by $\mathcal{T}_{\mathbb{R}^3}$ and $\mathcal{T}_{R_0}$ the metric topologies for $\mathbb{R}^3$ and $R_0$ associated with the metrics given by the corresponding distance functions. Apparently, measuring a point $z$ in space perfectly precisely requires $z$ to be an isolated point of $\mathbb{R}^3$. Similarly, unless time $t$ is an isolated point of $R_0$, it is impossible to measure $t$ perfectly precisely.

**Theorem 1.** *(The General Principle of Measurements): Precise space and time coordinates are practically unattainable by measurements, or equivalently, neither $\mathbb{R}^3$ nor $R_0$ have isolated points.*

**Proof.** Consider first an arbitrarily given $z \in S$, where $S \in \mathcal{T}_{\mathbb{R}^3}$ is arbitrary. Evidently, there is no $r > 0$ such that

$$B(z;r) \cap S = \{z\}. \tag{3}$$

Thus $\mathbb{R}^3$ has no isolated point. Now consider $t \in S$, where $S \in \mathcal{T}_{R_0}$ is arbitrary. An open "ball" now is an open interval

$$B(t;r) = (t-r, t+r). \tag{4}$$

There are two cases: $t = 0$, and $t > 0$. If $t = 0$, then $B(0;r) \notin \mathcal{T}_{R_0}$ for any $r > 0$, and there is no $S \in \mathcal{T}_{R_0}$ such that

$$S \cap B(0;r) = \{0\}. \tag{5}$$

Thus 0 is not an isolated point of $R_0$. If $t > 0$, there is no $r > 0$ such that

$$S \cap B(t;r) = \{t\}. \tag{6}$$

Thus $t$ is not an isolated point of $R_0$ either. Consequently, $R_0$ has no isolated point. $\square$

When physical events are considered in special relativity, the theorem proved above is also valid. Mathematically, the space-time of events in special relativity is a four-dimensional differential manifold called the Minkowski manifold, which is endowed with a topology, such that any subset of this manifold is either open or not in the usual sense. Thus the definition of an isolated point also applies to the Minkowski space-time manifold. Clearly, the Minkowski manifold has no isolated point.

Before the advent of quantum mechanics, physicists held a commonsense: "the same experimental conditions" always produce the same results. In other words, results produced by "the same experimental conditions" are deterministic. This commonsense is approximately true, because the experimental conditions in classical physics can be considered approximately the same, and random phenomena observed in classical physics are mainly due to lack of knowledge needed to describe physical situations that typically involve a large number of single microscopic objects; their behaviors are usually assumed to be independent. Randomness in such situations is explainable using statistical mechanics. The general principle of measurements is ignorable. Quantum mechanics changed this commonsense. Nowadays physicists hold a new commonsense: "the same experimental conditions" do not produce the same results in quantum physics, or equivalently, the results produced by "the same experimental conditions" in quantum physics are indeterministic [26]. However, this new commonsense is misleading and largely responsible for erroneously interpreted experimental results in quantum physics.

Of course, real numbers and other mathematical objects constructed based on real numbers are all precisely *defined*. But *the general principle of measurements is not about precise definitions of such mathematical objects; its significance is this: specified by precise space and time coordinates, "the same experimental conditions" are not physically meaningful.* Any random phenomenon in physics can only be observed in *different* repetitions of a given experiment under the experimental conditions that can only be approximately the same. According to the general principle of measurements, if "the same experimental conditions" are specified by precise space and time coordinates, then such experimental conditions are physically meaningless, because precisely defined coordinates are unattainable by practical measurements. Proved as a mathematical theorem, *the general principle of measurements does not involve issues concerning practical measurements raised by Bohr [2] or the accuracy of results obtained by measuring the values of space or time variables in various wave-functions.*

In an experiment with quantum objects of a given kind, mutually exclusive properties are actually observed in *different* repetitions of the experiment and correspond to *different* measurement outcomes associated with *different* objects of the same kind. But such properties are attached to an *imaginary* object. As a consequence of violating the general principle of measurements by taking precise space and time coordinates for granted to specify "the same experimental conditions", the imaginary object does not exist in the real world. Thus the origin of indeterminism in quantum physics is concealed by "the same experimental conditions". In various experiments involving quantum superpositions, indeterminism actually stems from violating the general principle of measurements and is not explainable using statistical mechanics.

## 6. Hilbert Space in Quantum Mechanics

The general principle of measurements paves the way for completing quantum mechanics within the framework of local realism. The mathematical setting for quantum mechanics is Hilbert space. In 1927, John von Neumann provided, for the first time, the definition of a *general* Hilbert space. Based on the *general* Hilbert space, von Neumann further provided an axiomatic formulation of quantum mechanics as its formal foundation. The name of "Hilbert space" is in honor of David Hilbert. At the beginning of the last century, Hilbert studied the classical prototype of what is known today as a Hilbert space in his work on the theory of integral equations. In functional analysis, mathematicians now denote this space by $\ell^2$. As shown below, the general principle of measurements allows quantum mechanics to be completed within the framework of local realism in a way consistent with the definition of the *general* Hilbert space.

Concepts used by von Neumann to define the *general* Hilbert space are all highly abstract notions and have no practical meanings. Specified by an inner product, orthogonality is a purely mathematical concept. Assigning practical meanings to orthogonality is unnecessary. Moreover, the logical relation between orthogonal vectors is not needed in the definition of the *general* Hilbert space. Elements of $\ell^2$, the prototypical Hilbert space, are infinite sequences of complex numbers. The logical relation between orthogonal vectors spanning $\ell^2$ is neither conjunction ("and") nor disjunction ("or"); it is not necessary to assign any practical meaning to the logical relation. Only for a given application, practically meaningful concepts are necessary to define a specific Hilbert space used to describe practically meaningful objects.

However, if conjunction ("and") is the logical relation between orthogonal vectors spanning a Hilbert space, the orthogonal vectors must *not* correspond to mutually exclusive properties simultaneously belonging to the same object; such an imaginary object is a consequence of violating the general principle of measurements by taking precise space and time coordinates for granted to specify "the same experimental conditions". As shown in the last section, the "the same experimental conditions" are not physically meaningful, and the imaginary object does not exist in the real world.

The space $\mathbb{R}^3$ in Euclidean geometry is a popular analogy to a Hilbert space in quantum mechanics. They are both Hilbert spaces; $\mathbb{R}^3$ is a Hilbert space with the inner product defined for Euclidean vectors; orthogonal vectors spanning $\mathbb{R}^3$ are orthogonal only in the sense of Euclidean geometry but do not represent mutually exclusive properties simultaneously belonging to any geometric object. Thus conjunction ("and") can serve as the logical relation between the orthogonal vectors spanning $\mathbb{R}^3$. The components of such vectors can be measured simultaneously. The measurements will not cause anything in $\mathbb{R}^3$ to collapse.

The *general* Hilbert space defined by von Neumann differs from any Hilbert space in quantum mechanics. The difference between the former and the latter is that the concept of orthogonality in the latter has a specific meaning: conjunction ("and") is the logical relation between orthonormal vectors, which purportedly represent mutually exclusive properties simultaneously belonging to the same physical object *before* measurements. The axiomatic formulation of quantum mechanics is questionable because of the specific meaning assigned to orthogonality. But von Neumann's definition of the *general* Hilbert space is still valid and allows disjunction ("or") to serve as the logical relation between orthogonal vectors spanning a Hilbert space for practical applications.

For a Hilbert space in quantum mechanics completed based on the general principle of measurements, the logical relation is disjunction ("or"). A physical object of a given kind can of course have mutually exclusive properties; it just cannot have such properties simultaneously. Thus, represented by orthonormal vectors spanning the Hilbert space in quantum mechanics with disjunction ("or") serving as the logical relation, *different* outcomes corresponding to *mutually exclusive* properties of the physical object are actually associated with *different* objects of the same kind; such objects are measured in *different* repetitions of a given experiment. Obtained by measuring the corresponding object, each *single* outcome reveals an "element of the physical reality" considered in the EPR argument under the assumptions of locality and realism [1]. Consequently, a value corresponding to the *single* outcome can be assigned to the object, even though the precise space and time coordinates used to measure it are unknown; the value can even be taken from a continuum and cannot be obtained by measurements, such as the position or momentum of a particle moving in space.

As shown above, based on the general principle of measurements, quantum mechanics can indeed be completed within the framework of local realism, such that the completed quantum theory is consistent with the definition of the *general* Hilbert space without changing the mathematical setting. In von Neumann's definition of the *general* Hilbert space, the axioms concerning various calculations required by quantum mechanics, including the calculations of probabilities and expectation values, will all remain unchanged. However, in von Neumann's axiomatic formulation of quantum mechanics, some axioms are questionable and should be removed. These axioms are irrelevant to the calculations and can only make quantum mechanics difficult to understand, such as those implying the purported completeness of quantum mechanics in its present form, the so-called inherently probabilistic nature attached by the Copenhagen interpretation to quantum mechanics, and inexplicable collapses of wave-functions triggered by measurements. The questionable axioms are responsible for bringing the existence of observers into the theory in its present form. Removing such axioms will significantly simplify the axiomatic formulation of quantum mechanics. See Section 10 for further discussion.

## 7. Consequences of Violating General Principle of Measurements

Violating the general principle of measurements is due to taking precise space and time coordinates for granted to specify "the same experimental conditions" in various experiments with quantum-mechanically described objects. The violation leads to erroneously explained experimental results. Because corresponding experimental results are incorrectly explained, the Copenhagen interpretation of quantum mechanics makes little sense in practice.

### *7.1. Consequences of Taking Precise Space Coordinates for Granted*

Consider the optical experiment designed to test the CHSH inequality [10]. Expressed as a quantum superposition, an "entangled state" describes the single pairs of correlated photons and is used to calculate the probabilities of obtaining the corresponding outcomes by measuring the polarizations of the correlated photons in the pairs, which implies the legitimacy of Born's probabilistic interpretation of wave-functions. Born's interpretation fails to account for indeterminism in quantum physics, although it can be used to calculate the probabilities correctly. Thus the failure of the CHSH inequality is inevitable when tested by actual experiments against quantum mechanics. The "entangled state" and the optical experiment depend on "the same experimental conditions" specified by precise space coordinates, which are the corresponding points on a unit sphere $U \subset \mathbb{R}^3$. This sphere $U$ should not be confused with the "Bloch sphere", which is not contained in $\mathbb{R}^3$.

The points on $U$ correspond to a) the polarizations as well as propagating directions of *different* photons detected in *different* repetitions of the experiment, and b) the orientations of the polarizers for measuring the polarizations of the photons. Taking the precise space coordinates for granted [10], the "entangled state" violates the general principle of measurements and is illegitimate. The indeterminism observed in the measurement outcomes is exactly due to lack of knowledge about the precise space coordinates used to specify "the *same* experimental conditions" for measuring the polarizations of *different* photons detected in *different* repetitions. Using statistical mechanics cannot explain this indeterminism.

### *7.2. Consequences of Taking Precise Time Coordinates for Granted*

Taking precise time coordinates for granted to specify "the same experimental conditions" can also conceal the origin of indeterminism in quantum physics and has caused much difficulty in understanding the quantum measurement problem concerning not only microscopic objects but also "macroscopic" objects [3,4]. As indicated by the general principle of measurements, the indeterminism is due to lack of knowledge about precise time coordinates in corresponding experiments.

Consider first the measurement problem with measuring a single microscopic object described by the wave-function $\psi = c_1\psi_1 + c_2\psi_2$ (see Section 1). Denote by $E = \{q_n, n \geq 1\}$ an ensemble of such objects. The objects are all described by the wave-function $\psi$. In other words, $E$ is a pure ensemble consisting of microscopic objects characterized by the same pure state. Einstein's argument can be better appreciated in this simple, ideal situation without any distraction caused by unnecessary technical details involving mixed states. According to the Copenhagen interpretation, each object in $E$ possesses exclusive properties represented by $\psi_1$ *and* $\psi_2$ at any time before an observer measures the object. As shown below, the Copenhagen interpretation violates the general principle of measurements and makes little sense in practice.

To see this, denote by $H(\psi_1, \tau)$ and $H(\psi_2, \tau)$ two propositions, where $H(\psi_1, \tau)$ means "$\psi_1$ represents the outcome obtained by measuring an element of $E$ at time $\tau$." The meaning of $H(\psi_2, \tau)$ is similar. In $H(\psi_1, \tau)$ and $H(\psi_2, \tau)$, the time $\tau$ is fixed to specify "the same experimental conditions". If time could be measured perfectly precisely, $H(\psi_1, \tau)$ and $H(\psi_2, \tau)$ would hold *simultaneously* in the corresponding experiment, which requires $\tau$ to be an isolated point of $R_0$. Because $R_0$ does not have any isolated point, the Copenhagen interpretation is not practically meaningful. The measurements are actually performed on different objects in $E$ at different, unknown times, rather than the specified time $\tau$.

Now consider the measurement problem with measuring the macroscopic object $Q$ with two of its macroscopically distinguishable states $Q^+$ and $Q^-$ (see Section 1). Experiments with such "macroscopic" objects typically involve a "time ensemble" (see Figure 3 in [4]). When measurements are performed on $Q$, the measurements are all performed on the same object. Let $H(Q^+, \tau)$ and $H(Q^-, \tau)$ be two propositions. The proposition $H(Q^+, \tau)$ states: "$Q^+$ is observed by measuring $Q$ at time $\tau$." The other proposition has a similar meaning. In $H(Q^+, \tau)$ and $H(Q^-, \tau)$, the time $\tau$ is fixed in the "time ensemble" to specify "the same experimental conditions" needed to measure $Q$ [4]. If time could be measured perfectly precisely, both $H(Q^+, \tau)$ and $H(Q^-, \tau)$ would hold *simultaneously* in the corresponding experiment, which requires $\tau$ to be an isolated point of $R_0$. But $R_0$ does not have any isolated point as indicated by the general principle of measurements, and $Q$ is actually measured in *different* repetitions of the corresponding experiment at different, unknown times rather than $\tau$ used to specify "the same experimental conditions".

## 8. Some Theoretical and Practical Implications of Completed Theory

With disjunction (“or”) serving as the logical relation between superposed orthonormal vectors, the notion of “quantum superposition” in the completed quantum theory will be denoted by “superposition (disjunction)”, which differs essentially from its counterpart in the current version of quantum mechanics. To avoid confusion, the notion of “quantum superposition” in the current version of quantum mechanics will be referred to as “superposition (conjunction)”. Violating the general principle of measurements can result in using an *imaginary* object described by a superposition (conjunction) to characterize *different* objects measured in *different* repetitions of a given experiment. No outcome is obtained by measuring the imaginary object, which is nonexistent in the real world.

The EPR argument reveals a contradiction in the conceptual foundations of quantum mechanics, namely, the truth of Heisenberg’s uncertainty relation implies the incompleteness of quantum mechanics in its present form, or equivalently, the completeness of quantum mechanics implies the falsity of Heisenberg’s uncertainty relation [1]. After quantum mechanics is completed within the framework of local realism, does the completed quantum theory imply the falsity of Heisenberg’s uncertainty relation? The answer is yes. In the real world, there is no particle described by a wave-function expressed as a superposition (conjunction), which violates the general principle of measurements and implies an inexplicable collapse of the wave-function triggered by a measurement performed on an *imaginary* particle. In contrast, using superposition (disjunction) to describe *different* particles of the same kind measured in *different* repetitions of the corresponding experiment, the completed quantum theory precludes inexplicable collapses of wave-functions and does imply the falsity of Heisenberg’s uncertainty relation.

In the optical experiment with *single* pairs of *correlated* photons [10], the pairs are described by the “entangled state”, which is a superposition (conjunction). For a pair of correlated photons so described, no polarization can be assigned to either photon if no polarization measurement is performed, and a measurement triggers an abrupt collapse of the “entangled state” [10]. This is a typical situation unspeakable in quantum mechanics. The “entangled state” cannot describe anything physically meaningful in the real world. According to Einstein’s separability principle, either of the correlated photons in each pair possesses its autonomous polarization state independent of the other photon, and measuring the polarization of either photon cannot affect the other photon. Consequently, corresponding to the autonomous polarization states *simultaneously possessed* by both correlated photons (i.e., *distant* components) in each *single* pair (i.e., a separable system) to be detected *jointly* in the real world, each *single* outcome is obtained in *one* repetition of the experiment, even though the precise space coordinates used to detect the pair are unattainable by measurements and unknown.

This is actually Einstein’s ensemble interpretation of a wave-function [13], if the wave-function is expressed as a superposition (disjunction). Different pairs of correlated photons with their autonomous polarization states are detected in different repetitions of the experiment; they form an ensemble described by the superposition (disjunction). According to the general principle of measurements, the indeterminism exhibited in the outcomes obtained by measuring the polarization states of the photons is due to lack of knowledge about precise space coordinates and cannot be explained by statistical mechanics. Violating the general principle of measurements brings about using an *imaginary* pair to characterize *different* pairs detected in *different* repetitions of the experiment. By explaining the indeterminism, the general principle of measurements is helpful to eliminate the observers from the axioms of quantum mechanics in its present form. Probabilities used in Einstein’s ensemble interpretation have nothing to do with the observers.

The way to complete quantum mechanics suggested in this article should not be considered as questioning the correctness of quantum-mechanically predicted probabilities. After quantum mechanics is completed within the framework of local realism, the axioms relevant to calculating probabilities and expectation values needed by quantum mechanics are all unchanged. This is an important difference between the completed quantum theory and any hidden-variables theory. According to Bell’s theorem [11], “a theory can achieve complete agreement with quantum mechanics only if it is non-local." This claim is incorrect. By providing the same probabilistic predictions of empirical results as those provided by quantum mechanics in its present form, the completed quantum theory can indeed achieve perfect agreement with the current version of the theory. In contrast, the predictions given by Bell inequalities derived by resorting to a hidden-variables theory differ from the quantum-mechanical predictions. More importantly, the completed quantum theory is local rather than non-local or super-deterministic. The above theoretical implications concerning the conceptual foundations of quantum mechanics will be further discussed in Section 10.

In addition to the theoretical implications, the completed quantum theory also has important practical implications concerning experiments in quantum physics. Such experiments require very expensive equipments; constructing the equipments consumes a huge amount of effort and time, thus performing the experiments needs a lot of money. For an experiment with quantum objects described by superpositions (conjunction), quantum mechanics in its present form and the completed quantum theory can both provide correct probabilistic predictions of empirical results. However, the current version of quantum mechanics can lead to tremendous waste of effort, time, and money, because of the erroneously interpreted experimental results caused by violating the general principle of measurement. In contrast, the completed quantum theory is helpful to avoid the waste.

## 9. Correlation Versus Non-Locality

Consider the experimental tests of Bell inequalities [9] with *single* pairs (i.e., separable systems of the same kind) of *correlated* photons (i.e., the corresponding distant components), where each separable system is measured in only *one* repetition of a given experiment. In the interpretation of the experimental results given by Bell's theorem, the *correlation* between *distant components* (i.e., correlated photons) of a separable system (i.e., a single pair) in Einstein's local-realist world view is confused with nonlocal-interaction in the world described by Bell's theorem. According to Bell's theorem, not only local realism but also Einstein's separability principle have to be rejected. The confusion must be clarified. The *correlation* between *distant components* of a separable system in Einstein's local-realist description of the world differs essentially from non-locality in the world described by Bell's theorem. The general principle of measurements can reveal the difference.

In the experimental tests of Bell inequalities [9], the "locality loophole" has been closed, which is relevant to the Einstein-Bohr debate. Other loopholes, such as those concerning detections of photons and various far-fetched interpretations of the experimental results, are not fundamental. Detection loopholes cannot disprove Bell's theorem or change the world it describes. The far-fetched interpretations are not the experiments themselves and will not be considered here.

As implied by a condition *necessary to observe any random phenomenon*, the *correlation* between *distant components* of a separable system in Einstein's local-realist description of the world is *deterministic*. The necessary condition is a banal fact: *any single measurement in only one repetition of an experiment makes no sense statistically.* This condition is ignored in the existing literature regarding the present status of the problem. Clearly, *jointly* detecting the correlated photons in a *single* pair will produce *one and only one* outcome in *one* repetition of the corresponding experiment; indeterminism cannot manifest itself in only one repetition. Thus the polarizations *simultaneously possessed* by *both* correlated photons in each pair can be detected *jointly*, and the *correlation* between the photons in each single pair must be *deterministic*.

Therefore, using superpositions (disjunction) rather than superpositions (conjunction) to describe the single pairs precludes collapses of "entangled states" triggered by measurements. Indeed, if there are no superpositions (conjunction), there will be no inexplicable collapses of wave-functions triggered by measurements. Compared to the *deterministic correlation*, non-locality implies the legitimacy of "entangled states", which amounts to presuming the legitimacy of quantum mechanics in its present form. Without non-locality, Bell's theorem cannot interpret the experimental results of testing Bell inequalities, which are expressed in terms of *statistical* correlations. By considering an example (Bertlmann's-socks), Bell almost realized the deterministic nature of quantum correlation (see Figure 1 in [24]). Bell's example is similar to the slightly different version of Einstein's non-quantum-theoretical illustration of the separability principle (see Table 1 in Section 2). But why is the *deterministic correlation* between *distant components* of a separable system in Einstein's local-realist description of the world mistaken for non-locality in the world described by Bell's theorem? There are three reasons.

First, Bell and his followers did not attempt to explain indeterminism in outcomes obtained by experiments involving superpositions (conjunction); they merely tried to "reinterpret quantum mechanics in terms of a statistical account of an underlying hidden-variables theory" [11] while keeping quantum mechanics in its present form intact. To reproduce the *statistical* predictions of quantum mechanics, Bell inequalities have to be expressed by *statistical* correlations. Secondly, the condition necessary to observe random phenomena is ignored. According to this condition, indeterminism cannot manifest itself in only *one* repetition of the corresponding experiment. Finally, "entangled states" used in the experimental tests of Bell inequalities violate the general principle of measurements. Consequently, an *imaginary* pair is used to characterize *different* pairs detected in *different* repetitions, and *mutually exclusive* properties corresponding to *different* outcomes are attached to the *imaginary* pair. Eventually, the *deterministic correlation* is mistaken for non-locality.

## 10. Discussion

Quantum mechanics is one of the greatest discovers in the history of science. But its conceptual foundations have been controversial since its inception and are still debatable even today. In the Einstein-Bohr debate, two issues disturbed Einstein very much: (i) the purported probabilistic nature of quantum mechanics, and (ii) observers appeared in the axioms of the theory rather than deduced from the axioms. Because quantum-mechanically predicted probabilities are always in good agreement with statistical data obtained by experiments, nowadays most physicists are no longer worried about the so-called probabilistic nature of the theory. However, the existence of observers in the axioms is still worrisome. In Newtonian mechanics, assumptions can be made about the Solar System, and one can deduce from the assumptions what observers will see when they look at the sky. But the observers are not part of the Newtonian laws of motion. However, the experimental results of testing Bell inequalities have forced physicists to make observers part of the axioms in quantum mechanics. For this reason, Weinberg worried about the conceptual foundations of the theory [27]: "we are stuck with a theory that works extraordinarily well, but whose foundations continue to puzzle us and which may not survive in its present form indefinitely into the future."

In fact, (i) and (ii) are closely related issues, as can be readily seen from Einstein's illustration of his separability principle mentioned in Section 2. Einstein's illustration is non-quantum-theoretical but can show why the quantum-mechanical way of thinking is incorrect (see Table 2 below). There are two boxes, I and II, which may serve as two spatially separated regions. One of the boxes (say box I) contains a single ball, and box II is empty. Before an *observer* lifts the lid of a box and looks inside, which box contains the ball is unknown. According to the quantum-mechanical way of thinking, if the observer does not choose to lift the lid of a box and look at its content, the ball is not really in either box, and the state of each box is completely described by a probability equal to 1/2 [13]. In contrast, Einstein's way of thinking based on his *separability principle* is this: the contents of the boxes are independent of one another; one of the boxes, along with everything having to do with its contents, is independent of whatever happens to the other box, and the observer does not play any role here.

**Table 2.** A quantum theorist's way of thinking.

| Box | Content in Box When Nobody Looks | Probability of Finding Ball in Box |
|---|---|---|
| I | unknown (unspeakable) | 1/2 |
| II | unknown (unspeakable) | 1/2 |

Probability appeared in Table 2 is not physically meaningful. If probability used here makes sense physically, a large number of box pairs will be needed, and an *observer* must prepare the boxes by putting a single ball *randomly* into one of the two boxes to form an ensemble. Clearly, the contents in the two boxes are *deterministically* correlated: if one box contains the ball, the other box must be empty. For each single pair of boxes in the ensemble, the deterministic correlation always exists. Because of this deterministic correlation, when lifting the lid of a box and looking inside, what the observer finds in the box must be deterministic: the box is either empty or contains the ball, and from the content of the box, the observer knows immediately the content of the other box.

Unlike the quantum-mechanical way of thinking (Table 2), Einstein's way of thinking and the discussion in the last paragraph indicate what causes the randomness and why the world is not intrinsically probabilistic. Although Einstein's illustration is non-quantum-theoretical, his separability principle implies an important hint for us to see a connection between the so-called probabilistic nature of quantum mechanics and observers in the axioms of the theory, where *observers are not laymen; they are physicists.* Indeterminism (or randomness) will not manifest itself in one repetition of a given experiment in quantum physics (or in any other discipline). For the purpose of this study, it is only necessary to consider the experiment in quantum physics. As *observers*, physicists design the experiment with quantum objects, use probability to describe indeterminism observed in the experiment, and interpret the experimental results according to quantum mechanics in its present form. Because they are not aware of the general principle of measurements when interpreting the experimental results, the physicists unconsciously make themselves part of the axioms. For example, it is quite easy to find papers by physicists under the title like "Is something there when nobody looks?" in the existing literature, where "something" may be the Moon or a quantum object. As can be readily seen below, the existence of observers can be eliminated from the axioms by explaining the indeterminism based on the general principle of measurements.

The non-quantum-theoretical illustration of Einstein's separability principle can be readily extended and used to analyze the quantum-mechanical interpretation of the perfect correlations observed in the experimental tests of Bell inequalities with technologies of modern optics (Table 3).

**Table 3.** Quantum-mechanical interpretation of perfect correlations.

| **Polarizations of $(\nu_1, \nu_2)$** | **Polarizations of $(\nu_1, \nu_2)$ When Nobody Measures** | **Probability Assigned to $(\nu_1, \nu_2)$** |
|---|---|---|
| (+, +) | unspeakable | 1/2 |
| (-, -) | unspeakable | 1/2 |

In the optical experiment with *single* pairs of *correlated* photons, two parallel polarizers are spatially separated for measuring the polarizations of the photons in the pairs denoted by $(\nu_1, \nu_2)$, where the pairs are described by an "entangled state", which is a superposition (conjunction) [9,10]. There are only two categories of polarizations obtained by measuring $(\nu_1, \nu_2)$, which are represented by (+, +) and (-, -). If no observers perform polarization measurements, then according to the quantum-mechanical interpretation, polarizations cannot be assigned to either of correlated photons in any single pair, and what can be assigned to each pair is the quantum-mechanically calculated probability. Moreover, polarization measurements performed by observers will abruptly trigger inexplicable collapses of the "entangled state" [9,10]. Such collapses of the "entangled state" triggered by measurements are nothing but what Einstein called "spooky actions at a distance". All such "spooky actions at a distance" are excluded irrefutably by Einstein's separability principle. Although the statistical correlations obtained from the quantum-mechanically calculated probabilities are in good agreement with the experimental data, it is the quantum-mechanical interpretation that not only attaches "the probabilistic nature" to quantum mechanics but also brings observers into the axioms of the theory. As shown in Section 5, the quantum-mechanical interpretation violates the general principle of measurements and cannot account for indeterminism in quantum physics due to the violation.

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According to Einstein's separability principle, either $\nu_1$ or $\nu_2$ possesses its autonomous polarization state, and measuring the polarization of either photon cannot affect the other photon. Corresponding to the autonomous polarization states *simultaneously possessed* by both $\nu_1$ and $\nu_2$ in each *single* pair $(\nu_1, \nu_2)$ to be detected *jointly* in the real world, each *single* outcome, (+, +) or (-, -), is obtained in *one* repetition of the experiment as illustrated in Table 4. But (+, +) and (-, -) can never be detected for the *same* single pair in the *same* repetition. This shows again what the "entangled state" can describe is only an imaginary pair rather than single pairs in the real world.

**Table 4.** Polarizations of $(\nu_1, \nu_2)$ measured in different repetitions.

| **Polarizations of $(\nu_1, \nu_2)$ Measured in a Repetition** | **Polarizations of $(\nu_1, \nu_2)$ Measured in Another Repetition** |
|---|---|
| (+, +) | (-, -) |

Table 5 illustrates Einstein's ensemble interpretation of the perfect correlations. Different pairs of perfectly correlated photons form an ensemble described by a superposition (disjunction). Compare Table 5 with Table 3. The comparison shows clearly the difference between the quantum-mechanical interpretation and Einstein's ensemble interpretation; the quantum-mechanical interpretation attaches the purported probabilistic nature to quantum mechanics, but Einstein's ensemble interpretation precludes the so-called probabilistic nature of the theory; although probabilities are used in both interpretations, the probabilities in Einstein's ensemble interpretation have nothing to do with observers in the axioms of quantum mechanics in its present form. The comparison also shows the difference between the completed quantum theory and the theory in its present form; the completed quantum theory is local-realist but can achieve complete agreement with the current version of the theory by providing the same probabilistic predictions of empirical results as those provided by quantum mechanics in its present form.

**Table 5.** Einstein's ensemble interpretation of perfect correlations.

| **Measured Polarizations of $(\nu_1, \nu_2)$ in Ensemble** | **Probability Assigned to $(\nu_1, \nu_2)$ in Ensemble** |
|---|---|
| (+, +) | 1/2 |
| (-, -) | 1/2 |

## 11. Conclusions

Einstein disagreed with the Copenhagen interpretation of quantum mechanics, which presumes the legitimacy of quantum superpositions, attaches "the probabilistic nature" to quantum mechanics, brings observers into axioms of the theory, and claims that quantum mechanics is already a complete theory. The legitimacy of quantum superpositions lies at the heart of the quantum measurement problem and is the essence of the Einstein-Bohr debate. Inspired by Einstein, Bell and his followers intended to complete quantum mechanics within the framework of local realism [16,17]. Regrettably, they adopted a problematic approach, which fails to capture the essence of the Einstein-Bohr debate and cannot reveal the essential difference between the *deterministic correlation* in Einstein's local-realist description of the world and non-locality in the world described by Bell's theorem. The *deterministic correlation* is between *distant components* of a separable system that satisfies the condition demanded by Einstein's separability principle [13]. Had Bell and his followers focused on explaining indeterminism in quantum physics rather than reinterpreting quantum mechanics, the regrettable situation might have been avoided. Described himself as a follower of Einstein, Bell hoped for better quantum theories than our current version of the theory, insisting that the theory in its present form was no more than a temporary expedient [16]; he would have been happy to see quantum mechanics completed within the framework of local realism without relinquishing Einstein's separability principle.

By explaining indeterminism in quantum physics, the general principle of measurements allows quantum mechanics to be completed within the framework of local realism while keeping the definition of a *general* Hilbert space unchanged, so the completed quantum theory can provide the same

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probabilistic predictions of empirical results as those provided by the theory in its present form. The general principle of measurements can also reveal the essential difference between the *deterministic correlation* and non-locality. In addition, using disjunction ("or") as the logical relation between superposed orthonormal vectors, the completed quantum theory precludes inexplicable collapses of wave-functions, eliminates observers from the axioms of quantum mechanics, and is intuitively comprehensible, thus alleviating much difficulty experienced by many people (including Bell [17]) in understanding the theory in its present form. Among various world views, Einstein's local-realist world view is correct.

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