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Categories of Nonlocality in EPR Theories and the Validity of Einstein's Separation Principle as Well as Bell's Theorem

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Abstract

Work on quantum entanglement is currently emphasizing the nonlocal nature of theories that attempt to explain spatially separated Einstein-Podolsky-Rosen (EPR) correlation experiments. It is frequently claimed that nonlocal instantaneous influences, or equivalently a breakdown of Einstein's separation principle, are a signature property of (quantum) entanglement. This paper presents a categorization of the various forms of nonlocality in physical theories. It is shown that, even for Einstein's theory of relativity, correlations of spatially separated measurements cannot be explained without the involvement of some nonlocal or global knowledge and facts. Instantaneous Influences at a distance are, however, in a special category of nonlocality and, as is well known, Einstein called them spooky. Following a separation of nonlocalities into four distinctly different categories 0, 1, 2, 3, with number 3 corresponding to theories containing instantaneous influences at a distance, I show that any theory of EPR experiments must be at least in category 1 or 2 and does not need to be in category 3. In particular, the Bell theorem, valid for category 0 theories, may be violated for categories 1 and 2 and does not require category 3 theories. Category 0 enforces Bell's theorem. However, it does not apply to relativistic theories of space like separated measurements.

Keywords

Bell's Theorem, Einstein's Separation Principle, EPRB Experiments

1. Introduction

The EPR Gedanken-experiments [1] were originally designed to show that quantum mechanics is either involving velocities higher than the speed of light in va-

cuum or is incomplete. Such experiments were later suggested by Bohm (EPRB), in a specific form, for correlated particles with spin and measurements with Stern-Gerlach magnets. The experiments have actually been performed with optical polarizers measuring correlated (commonly called entangled) photon pairs.

The incompleteness of quantum mechanics was suspected by Einstein, because of the possible existence of hidden variables in the theory of EPR experiments. However, John Stuart Bell [2] claimed that he could prove that no hidden variables can exist in any EPR-type theory that uses exclusively the physics of Einstein as opposed to quantum theory. (Bell used actually the phrase "classical physics" instead of the "physics of Einstein". The term "classical physics" is, however, not clearly defined and usually refers to physics that violates the Uncertainty Principle. Such violations are not permitted in the EPR Gedanken-experiment, which was constructed in a way to avoid violations of this established quantum principle.)

As a consequence of Bell's denial of the existence of hidden variables, the EPR logic leads necessarily to some violations of the limiting nature of the speed of light. This fact was only reluctantly accepted even by Bell himself, but is now accepted by a significant majority of the physics community who believes that entanglement does just that. It is widely assumed that instantaneous influences are exerted over arbitrary large distances between entangled particles or equivalently that entangled particles exhibit a "quantum nonlocality". They cannot be entirely separated but carry with them some properties that are rigidly connected to each other irrespective of space-like distances. Thus, Einstein's separation principle that is the basis of the EPR paper [1] is said to be violated by entanglement.

However, no experimental proof of instantaneous influences (or a violation of Einstein's separation principle) has ever been provided for any given entangled-particle-pair measurement. Nor can it ever be provided, because of the random outcome of the single measurement events. Any proof of instantaneity for a given pair would necessarily involve instantaneous information transfer at a distance, which contradicts the theory of relativity. Such possibility is indeed entertained by many science writers.

Experts on EPR questions, however, point to Bells theorem and to statistical experiments involving significant distances to justify their acceptance of such instantaneous influences. However, as we will see, Bells theorem depends sensitively on the actual meaning of the words "quantum nonlocality" as opposed to "local", words that are used when stating what the theorem means. A stalemate usually occurs at this point of discussions, because most of Bell's followers claim that the word "quantum nonlocality" is of a nature unknown to our macroscopic world and we can, therefore, not find any valid analogies about it.

It is the purpose of this paper to show that "nonlocalities" in physical theories (including Bell's) may be subdivided into 4 categories. The Bell theorem of the non-existence of hidden variables is shown to be valid in category 0 but may be violated in categories 1, 2 and 3. Only the theories of category 3 violate Einstein's

separation principle. This means that the Bell theorem is not sufficient to guarantee membership of any EPR theory in category 3.

2. Illustrations of the Nonlocal Content in Physical Theories

As the first example for nonlocal content consider Einsteins special relativity and corresponding experiments: we must assume that the speed of light in vacuum is the same everywhere in empty space. This nonlocal (global) knowledge is a postulate of special relativity. Furthermore and most importantly, any observable physical events in different macroscopic inertial systems are linked by their relative velocity and their theory must, therefore, involve nonlocal knowledge.

As a second example consider EPRB-type experiments and corresponding theories, which are about macroscopically detecting separate and distant measurement events corresponding to entangled pairs emanated from a common source. We encounter here the difficult task of asserting experimentally and theoretically which of the single detections have indeed originated from entangled pairs. The difficulties of this task arise because of the existence of quantum fluctuations that influence all measurements related to atomic and subatomic phenomena. This difficult task of pairing the single outcomes is the last step of the data formation process in EPRB experiments, which must produce data for the products of two distant measurement outcomes. That last step involves nonlocal knowledge and facts; a crucial point that is usually ignored.

It appears then that correlations of space-like separated measurements cannot be understood by a completely local theory, nor is the process of data formation completely local. However, Bell stated himself the following about the meaning of his **Theorem**: "But if [a hidden variable theory] is local it will not agree with quantum mechanics, and if it agrees with quantum mechanics it will not be local. This is what the [Bell] Theorem says".

Bell refers, of course, to the quantum mechanics of EPRB experiments and to experimental results that agree to a very good approximation with that quantum mechanics. Proving the Theorem involves a mathematical inequality [2] that contradicts quantum mechanics.

As we just have seen, all theories and experiments of spatially separated events must involve some nonlocal knowledge. Why, then, did Bell need a mathematical inequality to prove what he claims "the Theorem says"? The contradictions to Bells inequality [2] and similar Bell-type inequalities are the crux of Bells claim. One could restate Bells explanation of the meaning of his **Theorem** by:

"But if [a hidden variable theory] is local, it will obey Bell-type inequalities, and if it agrees with quantum mechanics it will not be local."

The above examples show, however, that nonlocal (global) knowledge is indeed involved in any non-trivial theory of correlations of separated systems and events. All EPRB-experimenters rely on some form of post-processing, which accomplishes the bringing together of the results of the single measurements and in itself requires a nonlocal knowledge of facts. Nonlocal (global) knowledge must be contained in any specific labelling of the experimental data that is used

for the pairing of distant events.

We must, therefore, ask what precisely the word "local" means in Bells theorem. Why is it not clear without any inequality and theorem that some nonlocality is involved in both theory and experimental data as soon as we talk about space-like separated measurements and their correlations? What kind of nonlocality did Bell actually identify by his inequality and why should this fact have any special significance? There also exist numerous text-book tutorials involving the two characters Alice and Bob, who have exclusively local knowledge and try to explain EPRB experiments. How can they work without any nonlocal knowledge and again what does nonlocal mean?

In order to answer these questions with precision, I propose the following categorization of local and nonlocal theories.

3. Categories of Nonlocality

I wish to define four mutually exclusive categories of locality or nonlocality of theories that correlate space-like distant events:

- **Category 0**: Any physical theory that exclusively uses local knowledge of facts and data that are immediately available to the local experimenters and only to them.
- **Category 1**: Any physical theory that uses nonlocal (global) knowledge of facts, which is precisely the same than (or physically equivalent to) the nonlocal (global) knowledge of facts that the formation and labeling of the experimental data necessarily involves. This category includes theories that consider the experimental processing of data, which originally have been obtained at two or more different locations, for the purpose of comparison.
- **Category 2**: Any physical theory that uses nonlocal (global) knowledge of facts beyond that of category 1 but is itself not contained in the theory-sets of category 3.
- **Category 3**: Any physical theory that involves a measurement event at one location that determines instantaneously the outcome of a measurement event at a space-like separated location. Both measurements must be related to two or more physical entities (such as electrons or photons) that are "nonlocally connected". The words "nonlocally connected" mean that the physical entities violate Einstein's separation principle as defined in [1]. This nonlocal connection is currently thought to describe the nature of entanglement.

As shown in the next section, categorizing the main theories of physics, including relativity and quantum mechanics, suggests the following epistemological acceptability of categories:

Theories of category 0 and 1 that are used to describe correlations of distant measurement events are entirely acceptable. Correlations of measurement events described by category 2 are acceptable, but call for investigations to transform the theory into category 1. Category 3 theories are the only theories that use nonlocal "knowledge" that is not exclusively about macroscopically measurable

facts. Therefore, theories of category 3 are not of the type that Mach found appropriate and venture into the realm of what Einstein called spooky. They can only be accepted if there is no viable theoretical path in categories 0, 1 and 2.

It was already discussed above and is illustrated in more detail below that there exist no nontrivial category 0 theories of correlations between space-like separated measurements. It will also be shown that the Bell theorem, which is clearly valid for category 0 theories, may be violated in theories of all other categories and does, therefore, not specifically require a theory of category 3.

4. Examples to Illustrate the Nonlocality-Categories

As a first example that illustrates nonlocal categories take Newtons theory of gravitation. This theory assumes an instantaneous gravitational force acting between the sun and planets. The experiments that attempt to confirm this theory, however, are all performed by optical observations, which have the speed of light in vacuum as upper limit. Newtons theory is, therefore neither of category 0 nor of category 1. Simplified model systems such as point-masses and a fixed sun may be put into category 2, with category 3 being a possibility that cannot necessarily be excluded for more complex models. Einstein transformed the theory of gravitation into category 1. The recent measurements of gravitational waves gave a brilliant confirmation to this fact.

Take as another example an experiment from Einsteins special relativity. Alice and Bob are flying in two separate spaceships. Each of their spaceships contains an identical clock fabricated before departure. Einsteins special relativity gives the theory of the clock-times that Alice and Bob may determine by measurements and observations. We do not need to repeat here Einsteins solution, which is given in many elementary texts. The theory uses only the global knowledge found by all actual experiments and that forms the basis of the experiments: the velocity of light in vacuum and the global validity of the same physical law independent of the uniform motion of the systems in question. Thus, according to our postulate, there is no need to suspect spooky influences. However, it is also clear that Alice and Bob could not determine the clock correlations without knowing anything of each other. The requirement of category 0 to use exclusively knowledge that is locally available to them also excludes the relative velocity of the other spaceship and the identity of the velocity of light in vacuum at all spatially separated locations. Membership in category 0 thus prevents any meaningful theory of clock rates that Alice and Bob would observe. For example, how could they form a theory for the probability that both clocks are pointing to times in the first quarter (12 - 3) without knowing anything about the other spaceship? How could they predict the clock-times when the spaceships are finally brought together again (compare to post-processing of data)? Actual measurements of the relative velocity of the other spaceship permits the explanation of the clock-times by a category 1 theory as Einstein has shown.

Many body quantum theory, our third example, is very complex. It certainly cannot be placed into category 0. Some quantum physics has used global gauge

fields, which would correspond to category 2 frameworks. Modern teachings tell us how global gauge fields may be promoted to local ones and put the theory into category 1, which is commensurate with the Machian design of quantum mechanics by some of its fathers. However, many researchers of the quantum entanglement area and all science writers, have moved quantum mechanics into category 3 on the basis of Bell's theorem; incorrectly as we will see.

5. Nonlocal Relativistic Factors Involved in EPRB Theories (Models)

From the above examples, we can deduce that the postulate of exclusively local knowledge (category 0) prevents Alice and Bob to find any relativistic theory of clock-rates in spaceships. Relativistic theories necessarily depend on the velocity of both spaceships (the relative velocity of the spaceships to each other). The return and reuniting of the spaceships involves also nonlocal factors. However, Einsteins relativity is clearly of category 1, because the relative velocity and the return of the spaceships are part of the experiments and the process to obtain the data (compare to post-processing of data in EPRB experiments).

It is worthwhile to note that the relativity of events in two or more space-like separated locations, taken in its most basic meaning of the word "relative", necessarily involves nonlocal facts. However, the relativity of space-like separated events does not mean that Einstein's separation principle is violated. Take for example a double-barrel that shoots bullets into two directions. The bullets hit wooden planks with different thickness and strength in two separate locations. The bullets are detected if and only if they break through the wooden planks. The question of how many pairs of bullets break through the planks on average cannot be theorized about if one does not know the thickness of the planks on both sides. Therefore, a theory of category 0 cannot explain this elementary experiment. (As an aside, the probability for both bullets of a pair to break through planks with different thickness is, in general, not equal to the product of the single probabilities to break through on the respective side (equality being a signature feature of Bell-type proofs.)

Deeper relativistic aspects come to light if we consider the actual interactions of the particles with the measurement equipment. Consider spin $\frac{1}{2}$ particles interacting with Stern-Gerlach magnets and attempt to explain the interaction in terms of Einstein's physics (we defer the quantization to a later choice of the range of possible experimental outcomes).

The single particles approaching the Stern-Gerlach magnet system obey a symmetry by rotations of 4π, while the macroscopic magnet-symmetry is for rotations by 2π. The total system of entangled pairs (in the singlet state) plus magnets has also a 2π rotational symmetry. Each single collision in the separate EPRB wings involves relativistic interactions of the incoming single particles (4π rotational symmetry) with those of the equipment (2π symmetry). Because of the existence of the (2π) rotational symmetry of the system as a whole, there must be

some "connection" for the macroscopic outcomes of the two separate single collisions that is noticeable over longer time periods. This connection must reflect, on average, the symmetry of the whole system (rotations by 2π).

If one aims, however, for a more detailed description of the measurement outcomes (data) including the single collisions, it is not sufficient to consider only the symmetry of the whole system. One needs then to consider the dynamics of the single collisions on each side and, in addition, a space-time correlation for the pair-outcomes describing the remnants of the overall symmetry "carried" by the single particles. A model of the single measurements on both sides that just includes the magnet directions without any trace of the space-time dynamics is certainly oversimplified. Even a very simple model of such a complex situation cannot work with a description that considers exclusively, in a dice-game-like manner, space-like entities. Any model that attempts to provide some realistic (if the word is permitted) description of the measurement outcomes needs at least to include some remnants of the space-time dynamics such as the measurement times in the laboratory system, as I have emphasized in several previous publications. The measurement time then carries the significance of representing the hidden or rather suppressed variable.

But what about Bell, who claims to have proven with his inequalities that hidden variables do not exist. Here lies one of my major points. Measurement times cannot and must not be included in Bell's theory. Walter Philipp and I have proven a theorem (theorem 2 in reference [3]) that means the following: Bell-type inequalities may be and even must be violated, if Bell's functions depend on the measurement times in addition to the magnet (polarizer) directions.

The quantum mechanical treatment has eliminated the use of space-time related effects for the single outcomes, because it does not consider the single outcomes and it uses the rotational symmetry of the whole system (2π) to calculate the averages over many experiments. The detailed dynamics of single particle equipment interactions are of no concern for what one can calculate, much to the advantage of the quantum theory. For interpretational questions, however, one must include invariably space-time, or equivalent concepts, in a more detailed way, because the macroscopic world of the data is currently only understandable in space-time or at least space and time. No better substitute has been offered yet. Space-time emerges, thus, as the "hidden" or rather suppressed variable. Its partial suppression in quantum theory permits us to "shut up and calculate".

6. Nonlocal Facts and Labeling of EPRB Measurement Data

To answer the question into which category theories of EPRB experiments may belong we need to know also nonlocalities that are necessarily used to label the data of these experiments.

Discussions of EPRB experiments frequently involve arguments with the two characters Alice and Bob that may be located arbitrarily far away from each other. They know everything about quantum physics and EPRB experiments but

they do not know anything about each other, because of the arbitrarily large distance between them, which may be light years. They must be able, however, to take data characterizing the EPRB measurements and label them. To be concrete, we consider the modern experiments of groups (e.g. [4]) that often use optical fibers to transmit and detect the single signals corresponding to photon pairs emanating from a common source and being detected after passing polarizers.

We assume here for the sake of argument that we have very long fibers, thousands of kilometers to each side so that a whole experimental sequence of measurements on many single pairs may be completed before Alice or Bob could obtain any information from each other. Alice and Bob, therefore, know nothing about each others measurements and have performed all their measurements independent from the other side. These measurements are taken with two randomly different polarizer directions denoted by unit vectors, $\boldsymbol{a}$ and $\boldsymbol{d}$ at Alice's location and $\boldsymbol{b}$ and $\boldsymbol{c}$ at Bob's, respectively. (Bells original theory deals with the special case $\boldsymbol{d} = \boldsymbol{b}$.)

Thus, we assume that Alice has been given the end of an optical fiber and a polarizer that measures the transmission of single photons from that fiber-end for a certain polarizer direction that Alice denotes e.g. by unit radius vectors $\boldsymbol{a}$ or $\boldsymbol{d}$ using her own coordinate system. Bob does the same with polarizer settings $\boldsymbol{b}$ or $\boldsymbol{c}$ defined in his respective coordinate system. They both create data when their detectors click and label the clicks with their own polarizer direction vector. (One can imagine an analogous experiment with spin 1/2 particles and Stern-Gerlach magnets.)

The goal of these EPRB experiments is to determine the frequency (related to the probability) of common clicks for the 4 different given setting pairs $\boldsymbol{a}, \boldsymbol{b}$; $\boldsymbol{a}, \boldsymbol{c}$; $\boldsymbol{d}, \boldsymbol{b}$ and $\boldsymbol{d}, \boldsymbol{c}$, in order to use these data to perform a so called Bell-test [4]. This determination is, as discussed above, impossible without the knowledge of further global facts. Assume for the moment, however, that we somehow are able to correctly pair detector clicks in the respective stations using a common vector space for the polarizer or magnet directions. Then we obtain certain frequencies and corresponding probabilities for each of the different polarizer-setting pairs.

Is it then possible to obtain the probabilities for detector clicks in both stations and compare them with the quantum result? The answer is no! We are still missing an important piece of information, because we do not know how the fibers have changed the polarization. To find this polarization change, we need to know for which pairs of polarizer settings all entangled pairs produce either a certain double click thus showing complete correlation (or equivalently anti-correlation as discussed in Bells original papers [2]). Knowledge of this latter fact is also an important part of Bells theory. Without this knowledge of the polarizer settings and detector ordering for complete correlation (or anti-correlation), neither Bells theory nor quantum theory can be related to the measurement results. How can Alice and Bob obtain this knowledge and label the data correspondingly? A relatively easy way is for Alice to take one setting-vector in

station one, say $\boldsymbol{a}$, and search in station 2 for the setting vector $\boldsymbol{a}^*$ that always leads to detector clicks when a click for $\boldsymbol{a}$ is obtained. This can, of course, only be achieved by letting Alice and Bob work together and know the outcomes of both stations, which represents a highly nonlocal procedure. To be complete, we also need to determine $\boldsymbol{d}^*$ as well as $\boldsymbol{b}^*$ and $\boldsymbol{c}^*$.

If we like to include the additional complication of quantum fluctuations and very large distances, we need to let Alice and Bob use certain additional tools, e.g. correlated clocks, in order to determine which of the clicks likely belong to pairs; or we need to invoke other additional global knowledge such as global thresholds. We can see from this discussion that nonlocality cannot easily be banned from the physics of correlations and we need a clear definition of which type of nonlocality is spooky as Einstein called it, and not scientifically permitted, and which type is permitted and must even be used to exorcise the spook and to demonstrate a natural correlation (or even causation).

7. Analytical Form of EPRB Theories of Category 3

EPRB theories that embrace Einstein's relativity and address separate measurements of entangled (or just correlated) pairs use the functions $A(\boldsymbol{j},\cdots)$ in one wing of the EPRB experiment and $B(\boldsymbol{j}',\cdots)$ in the other. The variable $\boldsymbol{j}$ may assume, for example, the values $\boldsymbol{a}$, $\boldsymbol{d}$ and $\boldsymbol{j}'$ may assume the values $\boldsymbol{b}$, $\boldsymbol{c}$. The domain of the functions includes thus a variable representing the magnet (or polarizer) settings and other variables that do not necessarily represent numbers but may represent more complex elements of physical reality such as space-time or objects in space-time.

The co-domain (range) of the functions is frequently taken as some outcome of spin-measurements such as up (+1) or down (−1) (quantization). However, it is clear that "up" is only well defined with respect to a given magnet (polarizer) setting and needs, from a more strict point of view, further labeling when multiple magnet (polarizer) settings are involved. It is not at all a priori clear whether or not "up (+1)" with an $\boldsymbol{a}$ direction of the magnet is physically or mathematically the same as "up (+1)" for a $\boldsymbol{b}$ direction of the magnet when multiple measurements with multiple magnet directions are involved. We do not address this point in most of the following discussions, but instead refer below to a publication that deals with complexities of the co-domain. Our main interests are related to questions regarding the domain of the functions A, B.

We ask ourselves the question whether there are distinct properties of the domain that signify the presence of instantaneous influences at a distance (a violation of Einstein's separation principle). The answer to this question is as follows.

The functions $A(\boldsymbol{j},\cdots)$ indicate the presence of instantaneous influences at a distance, or equivalently a breakdown of Einstein's separation principle, if and only if they are equivalent to functions $A'(\boldsymbol{j},\boldsymbol{j}',\cdots)$ *i.e.* functions that include explicitly the variable corresponding to the magnet settings of the other wing of the EPRB experiment. Obviously this condition is sufficient to describe an in-

stantaneous dependence on the magnet (polarizer) setting of the other side. It is also necessary, because otherwise no instantaneous change of the outcome value of A depending on magnet position can be achieved. Analogous reasoning applies for the functions B.

8. Category 1 and 2 EPRB Theories

In contrast to the immediately identifiable mathematical form of nonlocal category 3 theories, one cannot find a straightforward way to determine which mathematical form of functions puts the theory clearly into nonlocal category 1 or 2. The mathematical signatures of general global (nonlocal) knowledge that may be used in EPRB theories are numerous. Such signatures may be present in both domain and codomain of the functions. They also may shape the graph of the function and no specific and succinct criterium can be given for the function-forms that A, B must assume to be in nonlocal categories 1, 2 without detailed investigations of the involved specific physics.

Membership in a particular category other than 3 and 0 may only be deduced by extended physical reasoning. For example, the equipment settings $\boldsymbol{a}^*$ and $\boldsymbol{d}^*$ that guarantee the complete anti-correlation to the outcomes with Alices settings $\boldsymbol{a}$ and $\boldsymbol{d}$, respectively, must be known by Bob in order to properly label his measurement results. Therefore, a corresponding theory using Bobs nonlocal labeling belongs still to nonlocal category 1.

These complexities have impeded the detailed modeling of EPRB experiments by category 1 and 2 EPRB theories. However, several such theories are available in the literature and four examples are given in this section by pointing to references. It would be too complicated to report the detailed reasoning in these references but the main lines include the introduction of measurement time in the first two, the introduction of the mathematics of dynamical systems for the third and the explicit use of symmetries for the fourth. Finally I point to the conferences organized by Andrei Khrennikov for a world of further information.

In paper [5], the nonlocal knowledge involved is a globally known threshold for photon detection as well as a common vector space that is used in both EPRB wings to label the polarizer settings. Both pieces of global knowledge are also used by the experimenter and therefore the theory belongs to nonlocal category 1. No instantaneous influences are needed. The paper shows a clear contradiction to Bell-type inequalities and thus Bells theorem if it refers to nonlocalities of category 3.

In paper [6], the nonlocal knowledge involved is that of the magnet (polarizer) directions leading to perfect anticorrelation and the choice of a coordinate system for any given magnet or polarizer orientation of one experimental wing. This knowledge is used also by the experimenters and, therefore, up to this point the theory is of category 1. Furthermore, however, a global random function of time $rm(t)$ is used. The reason that Bell's theorem cannot capture such an approach related to measurement time is his assumption that puts all the variables of the domain of A as well as B on the same probability space. As shown by the

above mentioned theorem [3], measurement time and magnet settings cannot be on the same probability space. Global functions $rm(t)$ represent, of course, a remnant of nonlocality and are not used by experimenters. This puts the theory of this paper into category 2. However, such remnant nonlocalities (e.g. a global negative electron charge or any global symmetry) are completely different from instantaneous influences between one measurement event and a spatially distant event *i.e.* category 3.

For completeness, I like to add that the above considerations are not covering all the past and current work of dealing theoretically with EPRB experiments and finding contradictions to Bell-type inequalities.

For example, Luigi Accardi [7] has made early investigations of the dynamics of EPRB experiments in rigorous mathematical form.

Marian Kupczynski [8] has made many significant contributions and has recently closed the door on quantum nonlocality.

Joy Christian [9] used a more general codomain for the functions A, B as compared to the work described above, which only uses Bells original codomain of A, B = +1 or −1. Christian has attempted to show that his theory is within category 1. The complications of such assessment are beyond the scope of this discussion. However, as far as I understand it, Christians framework is at least in category 2 and certainly not in category 3.

Last, but not least, Andrei Khrennikov has made many important contributions in journals, books and conferences that he organized over decades. Many references to his work as well as papers of and references to other notables can be found in a special issue on this subject [10].

9. Conclusions

A quantum nonlocality violates Einstein's separation principle, and a theory that contains a quantum nonlocality is of category 3. I have shown, however, that nonlocal theories of category 1 and 2 exist that explain EPRB experiments and are based on Einstein's physics and the validity of his separation principle. These category 1 and 2 theories also agree with the quantum result for EPRB correlations and thus violate Bell-type inequalities. Bell's theorem stating that any local theory validates Bell-type inequalities is still correct. Completely local theories (category 0) do indeed validate Bell-type inequalities but cannot cover non-trivial relativisitc theories, because of the very definition of the word relativity, which requires viewing a system relative to another system (a nonlocal requirement). This nonlocality of relativistic theories is, however, not of category 3, which requires a breakdown of Einstein's separation principle.

A simplified explanation of these very formal distinctions and corollaries may be given in the following way. It is commonly assumed that entangled particles do not obey Einstein's separation principle, because the single particles carry properties that do not only depend on themselves but also on the other particles of the entangled system. This latter assertion is thought to invalidate Einstein's separation principle and is also seen as equivalent to the consequences of Bell's

theorem that requires nonlocality if one wishes to obtain the quantum result. These factors seem to present a shut and closed case for the Bell theorem and the concept of entanglement that violates Einstein's separation principle. Instead we are dealing here with a logical circle that can only be broken by the use of precise categorization as shown above.

The properties of the particle-pair that are not independent but nonlocal may just be properties of symmetry: the symmetry property of the single particles, the symmetry properties of the equipment with which they interact and the symmetry of the system as a whole. These various symmetries leave a trace in the single EPRB measurement outcomes for both measurement stations. As a consequence, the single-pair measurement outcomes are somehow linked to each other; a fact that may be described for interpretational purposes by the space-time dynamics of particle equipment interactions. In other words one needs to discuss details related to the dynamical interactions with the measurement equipment that quantum mechanics wisely avoids considering (at the risk of being incomplete). Considerations of many body interactions with the equipment help avoid any violation of Einstein's separation principle and remove the "weirdness" of quantum interpretations, at least as far as EPRB experiments and theories are concerned. Such considerations are, of course, of great complexity and reduce the effectiveness of quantum mechanics, which rests on the representation of polarizers and Stern-Gerlach magnets by unit vectors in three dimensional space. As I have shown, however, the mere addition of a time variable in the functions A and B (symbolizing correlated dynamic processes) is sufficient to avoid the pitfalls of model-oversimplification and allows violations of the Bell theorem in categories 1 and 2.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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