Commentary

On the Unreasonableness of the Quantum Nonlocality Debate

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We draw attention to an apparent, perplexing lack of logical rigor pervading the debate on quantum nonlocality. This paucity of rational thinking and compliance with the rules of logical inference leads to the production of unacceptable antinomies, which are widely and uncritically adopted by the scientific community without rigorous conceptual scrutiny.

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1. Introduction

This piece does not advocate arguments for or against the nonlocal character of quantum mechanics but rather describes puzzling contradictions and unjustified interpretations presented as proofs that purportedly resolve a problem that is mainly interpretational and conceptual.

Back in 1982, baffled by this situation, the distinguished philosopher of science Bas van Fraassen observed: *A reader as yet unfamiliar with the literature will be astounded to see the incredible metaphysical extravaganzas to which this subject has led*[1].

In our opinion, calling the inconsistencies and ad hoc fabricated interpretations "metaphysical extravaganzas" is, in many cases, a euphemism. In the first quarter of the 21st century, despite a Nobel Prize having been awarded for the empirical falsification of the Bell inequality, the situation has not improved.

Nonlocality is identified with the idea of instantaneous action at a distance:

Definition 1. *A theory is nonlocal if it predicts that what happens in a region of space has an immediate and instantaneous influence on another separate region without allowing a time delay for the propagation of the effect.*

We shall use the word “instantaneous” as a synonym for “superluminal.” The concept is theory-independent, i.e., it applies equally to classical and quantum physics. Thus, it makes perfect sense to ask whether or not quantum mechanics is a local theory. Quantum mechanics is argued to be nonlocal because some of its predictions seem to violate Definition 1.

Another concept that is ubiquitous in the debate on nonlocality is the concept of realism, as understood by physicists:

Definition 2. *Realism is a philosophical view, according to which external reality is assumed to exist and have definite properties, whether or not they are observed by someone*[2].

The realism tenet has its origin in the “elements of physical reality” concept introduced in 1935 by Einstein, Podolsky, and Rosen (EPR)[3]. Note that EPR realism is just an intricate form of requiring determinism since, by its very definition,

> *If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding lo this physical quantity.*

Note the relevant point is about “predicting with certainty” (determinism), and the rest is metaphysical speculation about what purportedly exists without actually being observed[4].

In Sections 2, 3, and 4, we review some widespread fallacies, sophisms, and unjustified interpretations surrounding the nonlocality problem. Section 5 discusses two different concepts of nonlocality. Finally, in Section 6, we go over some possible arguments in favor of quantum locality.

2. Nonlocality and EPR

The EPR paper is an argument for the incompleteness of quantum mechanics. The core of the EPR argument for incompleteness proceeds as follows.

Let LOC stand for locality and R stand for realism; the EPR argument is a reasoning proving that,

$$LOC \to R \tag{1}$$

Conforming to (1), every local theory must contain elements of physical reality and comply with realism. Quantum mechanics, being not deterministic according to the superposition principle and the Born rule, lacks elements of physical reality. Since nature itself is assumed to be local and quantum mechanics does

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not comply with realism, it cannot be the whole story, and eventually, it needs to be completed with hidden variables.

N. Bohr responded to the EPR paper[5] rejecting the EPR's realism criterion, confirming that quantum mechanics is indeed complete. According to the standard narrative, if QM stands for quantum mechanics, Bohr's rejoinder can superficially be reduced to a rejection of realism,

$$QM \rightarrow \neg R \tag{2}$$

The fallacy purportedly proving that quantum mechanics is a local theory because Bohr proved Einstein wrong is the claim that,

Fallacy 1. *Given the dichotomy between locality and realism, quantum mechanics is local because it is incompatible with the principle of realism.*

However, the claimed dichotomy is nonexistent. There is no explanation of how the rejection of realism restores locality to the predicted perfect correlation of distant events. The irony of claiming locality by rejecting realism is that those concepts are logically independent unless connected by (1) through the EPR argument, in which case the correct logical inference confirms quantum nonlocality.

Indeed, since (1) is equivalent to $\neg R \rightarrow \neg LOC$, (1) and (2) prove exactly the opposite,

$$QM \rightarrow \neg LOC \tag{3}$$

Fallacy 1 is a contradiction since any proof of non-realism purportedly proving Einstein wrong would be a proof of nonlocality. Thus, by confirming that quantum mechanics is indeed "not real," Bohr would be indirectly confirming its nonlocality.

We remark, however, that reducing Bohr's response to (2) is an unjustified oversimplification that cannot be attributed to Bohr. It would be puzzling that an intellectual giant like Niels Bohr committed such an obvious logical mistake and his opponent, another giant of 20th-century physics, did not notice it.

Bohr's response to EPR is generally considered obscure, hard to understand, and even almost unintelligible. Without claiming a full comprehension of Bohr's response, it seems clear that it cannot merely be reduced to (2).

A more cogent interpretation would be that he rejected the very conditions under which the implication (1) was obtained. At least that seems to have been Einstein's interpretation, who understood Bohr's response as denying the possibility of confronting what has been actually measured with what has not, calling Bohr's position solipsism.

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Thus, we do not claim that Bohr's response reduces to Fallacy 1. The fallacy emerges in the perfunctory form in which Bohr's response is usually exploited in the nonlocality debate to the point that it has acquired the status of an effective orthodox dogma to banish any consistent or erratic nonlocality argument.

Fallacy 1 also arises in the context of the Bell theorem that we shall discuss separately.

3. Nonlocality and the Bell theorem

The Bell theorem has proven to be a rich source of misinterpretations and fallacies. John Bell was an exceptionally clear-minded thinker, and he should not be blamed for all the antinomies attributed to him and his theorem.

3.1. Nonlocality and the "deterministic" Bell theorem

The first fallacy we analyze in this section is,

Fallacy 2. *The 1964 Bell's theorem proves that quantum mechanics is nonlocal.*

An attentive reading of his paper[6] shows that Bell did not claim Fallacy 2. In[6], Bell accepted the EPR reasoning of incompleteness from the beginning, as is clearly shown by part of the initial paragraph of his paper:

> *The paradox of Einstein, Podolski, and Rosen was advanced as an argument that quantum mechanics could not be a complete theory but should be supplemented by additional variables. These additional variables were to restore to the theory causality and locality.*

Thus, it is clear that, by accepting the EPR argument, he intended to "restore locality" to a theory that, being incomplete, was no longer local. At least according to Bell, and contrary to how most non-localist advocates interpret it, his theorem is a no-local-hidden-variable theorem, not a quantum nonlocality theorem.

3.2. Nonlocality and the "stochastic" Bell theorem

In 1975, Bell introduced a concept of locality that he called local causality, which, unlike the EPR reasoning, is a locality condition that applies to non-deterministic theories[7].

Only after proving that quantum mechanics violates local causality did Bell turn to the question of whether it is possible to add hidden variables to restore locality, preserving the statistical predictions of quantum mechanics. As in 1964, he found through his “locality inequality” that it was not possible to complete quantum mechanics to achieve locality.

Despite the universal claim, by localists and non-localists, that Bell intended to prove quantum nonlocality with his stochastic inequality, he explicitly and unambiguously argued that quantum mechanics violates local causality before introducing his inequality and hidden variables on at least two occasions[7][8]. So, there is sufficient textual evidence showing that Bell used the “locality inequality” only to restore locality by adding hidden variables and not to prove quantum nonlocality.

Thus, respecting Bell’s formulation, we can state the next fallacy,

Fallacy 3. *The stochastic Bell inequality proves that quantum mechanics violates local causality.*

Since, as we explained above, Bell disassociated his “locality inequality” from his quantum nonlocality argument, we also have the next related fallacy,

Fallacy 4. *Quantum mechanics is local because the Bell theorem assumes realism.*

Fallacy 4 is doubly unjustified. First, as we explained above and respecting Bell’s formulation, the Bell inequality can neither prove nor disprove quantum nonlocality. Second, since the stochastic version of the inequality is not based on determinism, it is not at all clear how the elements of physical reality could be involved, unless we arbitrarily impose the “realism dogma” by interpreting the common causes λ as pre-existing elements of reality.

Consistent explanations justifying quantum locality should dismiss the Bell inequality altogether and concentrate on rejecting the following concrete arguments:

a. The EPR nonlocality argument, as explained in Sec. 2, and noticing that the mere naive rejection of realism as usually understood only confirms nonlocality.
b. The violation of local causality by quantum mechanics, as argued by Bell in[7], or proved in[9]. In this case, the subterfuge of rejecting realism to justify locality is even more preposterous since local causality does not assume determinism. A consistent counterargument requires the discussion and eventual rejection of *Reichenbach’s common cause principle*[10].

4. The Bell inequality vs. Stapp’s inequality

Henceforth, we shall assume the Bell-CHSH inequality[11] as the Bell inequality. In 1971, Henry Stapp, realizing that the Bell inequality cannot be consistently considered a direct proof of quantum nonlocality, conceived a similar inequality to prove that quantum mechanics is indeed nonlocal[12].

Unlike the Bell inequality, Stapp's inequality was based on counterfactual reasoning and did not assume hidden variables. While the Bell inequality is a no-local-hidden-variable result, the Stapp inequality is a genuine quantum nonlocality argument.

Table 1 compares the characteristics of both inequalities. The Stapp inequality can be considered, along with the EPR reasoning and local causality, a third consistent argument for quantum nonlocality.[1]

Notwithstanding their different nature and objectives, the Stapp and Bell inequality formulations were soon conflated and confused, their methods and hypotheses merged in diverse ways, spawning some of the wildest ideas existing in the nonlocality debate.

Inequality type	Hidden variables	Quantum nonlocality	Quantum completion	Counterfactual reasoning
Bell	Yes	No	Yes	No
Stapp	No	Yes	No	Yes

Table 1. Bell vs. Stapp Inequality

Fallacy 5. *The Bell inequality relies on counterfactual reasoning.*

Counterfactual reasoning requires the comparison of what has happened with what would have happened if some initial condition had been different. That reasoning is present in the EPR argument and Stapp's inequality, incidentally, both arguments for quantum nonlocality.

The Bell inequality, being a completely different creature, is so stunningly straightforward that it looks suspicious, so some might want to upset it to make it look more convincingly sophisticated, and others perhaps to make it look untenable and easy to debunk.

The Bell inequality consists of the prediction of four different series of "actually performed" experiments $A_i B_k$ with four different setting combinations $i, k \in \{1, 2\}$, which are randomly selected, nothing else! You don't need to worry about what-if scenarios; you only need to compare what has actually happened in different series of experiments. The results obtained with the same settings are then averaged and finally summed,

$$S = \langle A_1 B_1 \rangle + \langle A_1 B_2 \rangle + \langle A_2 B_1 \rangle - \langle A_2 B_2 \rangle \tag{4}$$

The bound predicted for the series of experiments (4) depends on the theory used to make those predictions. Hidden variable theories predict

$$|S| \leq 2 \tag{5}$$

while quantum mechanics predicts $|S| \leq 2\sqrt{2}$, end of story. The complicated stuff is left for the experimentalists to empirically test the predicted results.

4.1. Emergence of the counterfactual claims

There is no place for counterfactual reasoning when predicting four series of experiments that are assumed to have been actually performed, despite abundant claims to the contrary[13][14][15][16][17][18][19][20][21][22].

We shall see that this misunderstanding arises from confounding the algebraic steps of the mathematical derivation with the requirements of an actual experimental test.

For the sake of simplicity, we shall assume a deterministic hidden variable model. According to this model, the predicted average for a series of experiments with setting $i, k \in \{1, 2\}$ is

$$\langle A_i B_k \rangle = \int A_i(\lambda) B_i(\lambda)\, \rho(\lambda)\, d\lambda \tag{6}$$

Leaving aside the difficulties and technical complexities of the real experiments, to test the inequality, all the experimentalist has to do is perform a series of experiments varying the two settings i, k randomly and registering the results until they collect a sufficient amount of data to evaluate the averages (6) for each of the four possible setting combinations, and finally add the values to obtain (4).

Once it is clear what we have to do in the laboratory to obtain (4), to derive the hidden variable prediction we need to push the algebra a little bit further, replacing (6) in (4) and remembering that $A_i(\lambda) = \pm 1$, $B_k(\lambda) = \pm 1$:

$$S = \int A_1(\lambda) B_1(\lambda)\, \rho(\lambda)\, d\lambda + \int A_1(\lambda) B_2(\lambda)\, \rho(\lambda)\, d\lambda \tag{7}$$

$$= + \int A_2(\lambda) B_1(\lambda)\, \rho(\lambda)\, d\lambda - \int A_2(\lambda) B_2(\lambda)\, \rho(\lambda)\, d\lambda \tag{8}$$

$$S = \int [A_1(\lambda) B_1(\lambda) + A_1(\lambda) B_2(\lambda) + A_2(\lambda) B_1(\lambda) - A_2(\lambda) B_2(\lambda)]\, \rho(\lambda) d\lambda \tag{9}$$

$$S = \int [\, A_1(\lambda) [(B_1(\lambda) + B_2(\lambda)] + A_2(\lambda) [B_1(\lambda) - B_2(\lambda)]\,]\, \rho(\lambda) d\lambda \tag{10}$$

$$|S| \leq 2 \tag{11}$$

The claim that the Bell inequality requires counterfactual reasoning arises from confounding the algebraic steps given by equations (7)$\sim$(11) with what is actually needed in the laboratory.

All the steps of the algebraic derivation are allowed by mathematical properties and should not be interpreted as an experimental protocol that the experimenter has to follow literally to falsify the predicted bound (5). However, in the algebraic step (9), the expression in square brackets is,

$$A_1(\lambda)B_1(\lambda)+A_1(\lambda)B_2(\lambda)+A_2(\lambda)B_1(\lambda)-A_2(\lambda)B_2(\lambda) \tag{12}$$

When (12) is interpreted as a step that the experimentalist has to actually reproduce in the laboratory literally, instead of a mere arithmetic manipulation, we immediately encounter an experimental impossibility.

Indeed, when the algebraic step (12) is interpreted as an experimental protocol, it requires different measurements with the same hidden variables. However, the experimenter has no control over the hidden variables, and we do not even know if they exist. All that the model assumes is that each entangled pair corresponding to measurements $A_i(\lambda)$ and $B_k(\lambda)$ is made of the same hidden variable λ.

There is no way for the experimentalists to reproduce (12) in the laboratory when interpreted as an experimental protocol to be followed literally; however, that did not deter people from interpreting it as Stapp interpreted a similar expression in his inequality[12]:

> *Of these eight numbers, only two can be compared directly to experiment. The other six correspond to the three alternative experiments that could be performed but were not.*

Although the former counterfactual interpretation makes perfect sense for Stapp's approach to his inequality, for the falsifiable Bell hidden variables inequality, the counterfactual recipe is experimentally untenable and theoretically meaningless.

In any case, if some physical explication is required for the terms appearing in step (12), it would be that they correspond to four different results of actual experiments that have been randomly performed, and later, by the commutative and associative properties of the arithmetic operations, were grouped as in (12) by the same value of λ. The last interpretation is indeed plausible since only a finite number of "effective" hidden variables exist for the Bell-CHSH experimental arrangement[23].

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4.2. Emergence of counterfactual definiteness

Although Counterfactual Definiteness (CFD) is supposed to be a rigorous technical term that expresses realism, its use is ambiguous, so it is necessary to clarify the meaning that we shall adopt in this discussion.

Some use the term Counterfactual Definiteness (CFD) as a synonym for counterfactual reasoning. Others consider CFD a sort of EPR realism, but going even further regarding the properties of things that we do not observe but presumably exist[24]:

Definition 3. *CFD is the ability to speak "meaningfully" of the definiteness of the results of measurements that have not been performed (i.e., the ability to assume the existence of objects, and properties of objects, even when they have not been measured). ......In such discussions "meaningfully" means the ability to treat these unmeasured results on an equal footing with measured results in statistical calculations. It is this (sometimes assumed but unstated) aspect of counterfactual definiteness that is of direct relevance to physics and mathematical models of physical systems and not philosophical concerns regarding the meaning of unmeasured results.*

There is at least one more connotation that seems to be somehow different, but all are related to some form of counterfactual reasoning. Here we shall deal only with definition 3, which leads to the following fallacy,

Fallacy 6. *Violation of the Bell inequality proves counterfactual definiteness is false.*

The obvious reason the above statement is fallacious is that the Bell inequality has no say on things that have not been actually measured. However, the assertion is so stunningly baffling that a few comments are in order.

We chose to use definition 3 because it bluntly states the core of the problem: *It is this (sometimes assumed but unstated) aspect of counterfactual definiteness that is of direct relevance to physics and mathematical models of physical systems and not philosophical concerns regarding the meaning of unmeasured results.*

So, by dismissing the conceptual analysis as "philosophical concerns," it assumes a *"shut up and calculate"* attitude, declaring that once a mathematical expression is written, all conceptual problems become irrelevant. This shut-up-and-calculate pragmatism proved to be very successful[25], but pursuing it without restrictions can lead to nonsense. The situation reminds us of a famous quote attributed to Carl Sagan: *"It pays to keep an open mind, but not so open your brains fall out."*

In any case, CFD is untestable because the theoretical derivation is obtained under the assumption that only one-third of the data comes from the results of actual experiments and the rest, three-quarters, are supposed to exist without being actually measured. Comparing this prediction with the result obtained through real experiments is meaningless because, in this case, 100% of the data come from actually performed experiments.

Let us rehearse a little logical exercise and see the plausibility of CFD:

- Assume we perform an experimental Bell-type test and we obtain $|S| \leq 2$. Would that confirm that a single particle has two different values of angular momentum because realism is true? Would that mean the unmeasured values of one-third of the measured particles materialized in the other three-quarters of the actually measured particles during the experiment?
- Now, assume that we obtain $|S| > 2$. Would that mean that realism is false because we did not find the unmeasured values? i.e., they did not materialize and transform into three-quarters of the particles we did measure in the experiment.

Furthermore, it is ironic that we never observe in macroscopic classical physics a single object possessing two different angular or linear velocities simultaneously. That claim seems to be more akin to quantum physics via the superposition principle.

4.3. Emergence of incompatible experiments

A related deviant interpretation associated with expression (12) is that it purportedly requires the measurement of incompatible observables[21][26][27].

Any argument requiring the simultaneous measurements of incompatible quantities contradicts orthodox quantum mechanics and should be immediately dismissed without further ado, be it the Bell inequality or the Stapp inequality.

We could blame Bell and Stapp for the heresy of daring to claim quantum nonlocality. Yet it would be unjustified to accuse them of having assumed the simultaneous measurements of incompatible observables or, relatedly, requiring a sequence of measurements on the same particle.

We surmise that the only way to come up with such a claim is the misinterpretation of (12) that, by the way, appears in both inequalities, but in different contexts.

The first such claim that we know of was made in 1972[28]. At the request of an editor, Bell succinctly commented on the criticism[29]:

The objection of de la Peña, Cetto, and Brody is based on a misinterpretation of the demonstration of the theorem......But by no means. We are not at all concerned with sequence of measurements on a given particle, or of pairs of measurements on a given pair of particles. We are concerned with experiments with which for each pair the "spin" of each particle is measured once only.

We are afraid that Bell's explanation to De La Peña et al. was not strong enough to prevent it from becoming a recursive misinterpretation, which became an endemic problem for correctly assessing the Bell inequality's implications.

Recently, some researchers had the original idea of using weak measurements to avoid the collapse of the wave function and perform more than one measurement on the same particle[21], as suggested by de la Peña, Cetto, and Brody. Although the experimental setup is remarkable, and we ignore the interpretation and possible applications of such experiments, we are certain that they do not test the Bell inequality.

However, the explanation given in[30] to justify the two sequences of measurements on the same particle was the use of the quantum identity,

$$\langle A_1B_1\rangle + \langle A_1B_2\rangle + \langle A_2B_1\rangle - \langle A_2B_2\rangle = \langle A_1B_1 + A_1B_2 + A_2B_1 - A_2B_2\rangle \tag{13}$$

The l.h.s of (13) is what Bell-type experiments actually measure, while the expression,

$$A_1B_1 + A_1B_2 + A_2B_1 - A_2B_2 \tag{14}$$

was measured in the experiment reported in[21] through successive weak measurements on the same pair of entangled particles. So, they claim, they indeed were testing the l.h.s of (13) that represents the usual Bell-CHSH experiment.

In[31], Bell noted that the identity (13) is a quite peculiar property of quantum mechanics. The sum of incompatible observables (14) represents an observable that is none of the individual terms in (14) and represents a completely different experiment that cannot be performed by individually measuring its terms. Bell presented the following example:

> A measurement of a sum of noncommuting observables cannot be made by combining trivially the results of separate observations on the two terms - it requires quite a distinct experiment. For example the measurement of σ_x for a magnetic particle might be made with a suitably oriented Stern-Gerlach magnet. The measurement of σ_y would require a different orientation, and of $(\sigma_x + \sigma_y)$ a third and different orientation.

Thus, it is clear that the l.h.s. of (13) cannot be obtained by individually measuring each of the incompatible observables of (14), hence the following fallacy:

Fallacy 7. *The Bell inequality requires the simultaneous measurement of incompatible observables or successive measurements on the same particle.*

5. Two different concepts of nonlocality

Here we rehearse an explanation of why most non-localists claim that Bell's "locality inequality" is proof of quantum nonlocality, contradicting Bell's own understanding of his inequality as a no-go theorem for local hidden variables.

A careful reading of Bell's manuscripts reveals that he conceived a different concept of nonlocality than most nonlocalists employ. Bell's nonlocality concept is the following:

Definition 4. ***Bell's nonlocality****: A physical theory is nonlocal when it lacks an explanation for its predicted perfect correlations.*

In the case of the EPR reasoning, as explained by Bell in[6], when an arbitrary choice in laboratory A instantaneously produces a different result in a distant laboratory B, to avoid action at a distance, the outcomes must have been already predetermined. Note Bell's careful use of the word "predetermined" (determinism) instead of "preexisting," thus avoiding the infamous "elements of physical reality" metaphysical speculation.

In the case of local causality, the requirement of determinism is excused by requiring instead a common cause explanation[10]. Such an explanation is also absent in quantum mechanics[7][9]. Einstein's and Bell's position was that since no local explanation exists, the only option left is "action at a distance" unless one adds hidden variables that could locally explain such "spooky" influences.

Without asserting that a local explanation is impossible within quantum mechanics, with a few exceptions, we are not aware of a consistent explication given by advocates of locality. Fallacy 1 seems to be the universal locality argument wielded by localists.

According to Bell's (and Einstein's) concept of nonlocality, the fact that a physical theory is nonlocal does not imply that nature itself is, unless it is impossible to add hidden variables either preserving its indeterminism (local causality) or turning it deterministic (EPR).

On the other hand, nonlocalists claiming that quantum mechanics is nonlocal because it violates the Bell inequality conceive of the nonlocality concept differently. For them, a theory becomes nonlocal only after proving that it is not possible to add hidden variables to explain its correlations.

The above observations show that, by dismissing Bell's careful approach to the nonlocality issue, nonlocalist advocates exacerbate the polemic, inadvertently facilitating the realism dogma excuse.

Certainly, to a great extent, the radical disagreement and endless discussions between localists and nonlocalists are because nonlocalists dismiss Bell's definition 4 of nonlocality, sidestepping the previous discussion of whether orthodox quantum mechanics is already nonlocal. Since, for localists, quantum mechanics itself is already local, nonlocality only emerges as a consequence of adding hidden variables that are foreign to quantum theory.

To make things worse and muddy the waters even more, localists invariably invoke the realism dogma as the culprit for the classical prejudices that, presumably, localists cannot overcome[32][33][34].

6. Quantum locality

We mentioned three consistent arguments for quantum nonlocality, namely, the EPR reasoning, local causality, and Stapp's inequality.

Here, we briefly mention what could be some consistent arguments for quantum locality in the sense of Bell's nonlocality as given in definition 4.

We start with counterarguments rejecting the three arguments for quantum nonlocality. The EPR reasoning and Stapp's inequality arguments can be blocked by rejecting the possibility of counterfactual reasoning. Bohr's reply to EPR seems to go in that direction by prohibiting the possibility of confronting the result of an experiment that we have performed with that which we have not.

Likewise, the violation of local causality by quantum mechanics can be dismissed by rejecting *Reichenbach's common cause principle*[10]. This is tantamount to rejecting that perfect correlations need an explanation and rejecting causation.

Whether quantum correlations need explanations was considered by Bell, but he thought that: *The scientific attitude is that correlations cry out for explanation*[7]. However, it is also possible to take the opposite position: *So pervasive has been the success of causal models in the past, especially in a rather schematic way at a folk-scientific level, that a mythical picture of causal processes got a grip on our imagination*[1].

A related third argument for quantum locality could be to postulate that operational quantum mechanics is local. This position is empirically consistent thanks to the no-signaling property of quantum mechanics and, of course, accepting that correlations do not need explanation.

7. Conclusions

We exposed widespread fallacies and inconsistencies plaguing the quantum nonlocality debate.

Although it is hard to understand the degree of unreasonableness reached by scientists and philosophers trained in rigorous logical thinking, part of the chaotic situation is owing to the lack of a clear definition of fundamental concepts such as locality, nonlocality, and the central role given to rather irrelevant metaphysical tenets such as EPR realism and counterfactual definiteness that end up being uncritically adopted as dogmas.

Footnotes

1 A detailed discussion of Stapp's inequality can be found in [4].

References

1. a, b *Van Fraassen BC (1982). "The Charybdis of Realism: Epistemological Implications of Bell's Inequality." Synthese. **52**:25–38. doi:10.1007/BF00485253.*
2. ^ *Clauser JF, Shimony A (1978). "Bell's Theorem. Experimental Tests and Implications." Rep Prog Phys. **41**(12):1881–1927. doi:10.1088/0034-4885/41/12/002.*
3. ^ *Einstein A, Podolsky B, Rosen N (1935). "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" Phys Rev. **47**:777–780. doi:10.1103/PhysRev.47.777.*
4. a, b *Lambare JP (2022). "On the Meaning of Local Realism." Found Phys. **52**(98, 5). doi:10.1007/s10701-022-00618-1.*
5. ^ *Bohr N (1935). "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?" Phys Rev. **48**:696–702.*
6. a, b, c *Bell JS (1964). "On the Einstein-Podolsky-Rosen Paradox." Physics. **1**:195–200. doi:10.1103/PhysicsPhysiqueFizika.1.195.*
7. a, b, c, d, e *Bell JS, Aspect A (2004). "The Theory of Local Beables." In: Speakable and Unspeakable in Quantum Mechanics: Collected Papers on Quantum Philosophy. Cambridge: Cambridge University Press. pp. 52–6*

2. doi:10.1017/CBO9780511815676.001.

8. ^Bell JS (2001). "La Nouvelle Cuisine." In: Bell M, Gottfried K, editors. John S Bell on the Foundations of Quantum Mechanics. Farrer Road, Singapore: WORLD SCIENTIFIC. pp. 216–234. ISBN 981-02-4687-0.
9. a, bLambare JP (2025). "On the Polemic Assessment of What Bell Did." arXiv. doi:https://arxiv.org/abs/2506.22915.
10. a, b, cReichenbach H (1956). The Direction of Time. Mineola, N.Y.: Dover Publications.
11. ^Clauser JF, Horne MA, Shimony A, Holt RA (1969). "Proposed Experiment to Test Local Hidden-Variables Theories." PhysRevLett. **23**(15):880. doi:10.1103/PhysRevLett.23.880.
12. a, bStapp HP (1971). "S-Matrix Interpretation of Quantum Theory." Phys Rev D. **6 B**:1303–1320. doi:https://doi.org/10.1103/PhysRevD.3.1303.
13. ^Eberhard P (1977). "Bell's Theorem Without Hidden Variables." Nuov Cim. **38 B**:75–79.
14. ^Peres A (1978). "Unperformed Experiments Have No Results." Am J Phys. **46**:745–747. doi:10.1119/1.11393.
15. ^Herbert N, Karush J (1978). "Generalization of Bell's Theorem." Found Phys. **8**:313–317. doi:10.1007/BF00715216.
16. ^Skyrms B (1982). "Counterfactual Definiteness and Local Causation." Philos Sci. **49 B**:43–50. doi:10.1086/289033.
17. ^Dickson M (1993). "Stapp's Theorem Without Counterfactual Commitments: Why It Fails Nonetheless." Stud Hist Philos Sci A. **24**(5):791–814. doi:https://doi.org/10.1016/0039-3681(93)90064-Q.
18. ^Blaylock G (2010). "The EPR Paradox, Bell's Inequality, and the Question of Locality." Am J Phys. **78**:111–120. doi:10.1119/1.3243279.
19. ^Wolf S (2015). "Nonlocality Without Counterfactual Reasoning." Phys Rev A. **92**:052102. doi:10.1103/PhysRevA.92.052102.
20. ^Kupczynski M (2020). "Is the Moon There If Nobody Looks: Bell Inequalities and Physical Reality." Front Phys. **8**:273. doi:10.3389/fphy.2020.00273.
21. a, b, c, dVirzì S, Rebufello E, Atzori F, Avella A, Piacentini F, et al. (2024). "Entanglement-Preserving Measurement of the Bell Parameter on a Single Entangled Pair." Quantum Sci Technol. **9**(4):045027. doi:10.1088/2058-9565/ad6a37.
22. ^Hance JR (2024). "Counterfactual Restrictions and Bell's Theorem." J Phys Commun. **8**(12):122001. doi:10.1088/2399-6528/ad9b6d.

23. ^Lambare JP, Franco R (2021). "A Note on Bell's Theorem Logical Consistency." Found Phys. **51**(84). doi:10.1007/s10701-021-00488-z.

24. ^Wikipedia contributors (2025). "Counterfactual Definiteness — Wikipedia, the Free Encyclopedia." Wikipedia. https://en.wikipedia.org/w/index.php?title=Counterfactual_definiteness&oldid=1282425387.

25. ^Kaiser D (2014). "History: Shut Up and Calculate!" Nature. **505**:153–155. doi:10.1038/505153a.

26. ^Muynck WM, De Baere W, Martens H (1994). "Interpretations of Quantum Mechanics, Joint Measurements of Incompatible Observables, and Counterfactual Definiteness." Found Phys. **24**:1589–1664.

27. ^van Heusden EFG, Nieuwenhuizen TM (2019). "Simultaneous Measurement of Non-Commuting Observables in Entangled Systems." Eur Phys J Spec Top. **227**:2209–2219. doi:10.1140/epjst/e2019-800216-2.

28. ^De La Peña L, Cetto AM, Brody TA (1972). "On Hidden-Variable Theories and Bell's Inequality." Lett Nuovo Cimento. **5**:177–181. doi:10.1007/BF02815921.

29. ^Bell JS (1975). "Locality in Quantum Mechanics: Reply to Critics." Epistemol Lett. (7):2–6.

30. ^Genovese M, Piacentini F (2025). "Reply to "Comments on 'Consequences of the Single-Pair Measurement of the Bell Parameter'."" Phys Rev A. **112**:066203. doi:10.1103/prqc-2jbw.

31. ^Bell JS (1966). "On the Problem of Hidden Variables in Quantum Mechanics." Rev Mod Phys. **38**:447–452.

32. ^Gisin N (2012). "Non-Realism: Deep Thought or a Soft Option?" Found Phys. **42**:80–85. doi:10.1007/s10701-010-9508-1.

33. ^Laudisa F (2012). "The Uninvited Guest: "Local Realism and the Bell Theorem."" In: de Regt HW, Hartmann S, Okasha S, editors. EPSA Philosophy of Science: Amsterdam 2009. Dordrecht: Springer Netherlands. pp. 137–149. ISBN 978-94-007-2404-4.

34. ^Norsen T (2007). "Against "Realism."" Found Phys. **37**:311–454. doi:10.1007/s10701-007-9104-1.

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