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Review Article

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Principles of Physics and Violation of Bell Inequalities in Relativistic Experiments

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Abstract
Examples of violations of Bell inequalities in Special relativity theory (SRT) have led to the need to look for the causes of violations outside of quantum mechanics (QM) and possibly outside of physics. The ability to derive Bell inequalities (BI) from set properties allows us to find the necessary condition for violations: the relativity of sets. At the same time, a necessary condition of a physical theory is the subjective independence (SI) of its propositions. This kind of objectivism, together with the principle of a priori maximum possible ignorance (AMPI), leads to the use of flat spaces in fundamental theories such as QM and SRT, where the principles of SI and AMPI can be implemented. In turn, the measurable quantities represented in spaces turn out to be relative. In this respect, SRT is not much different from QM. This proximity predetermines BI violation in both cases and in both cases the violation of BIs confirms the subject-independent nature of physics. In a classic Gedankenexperiment was demonstrated, that the violation of BI does not contradict the presence of hidden parameters if they are represented by relative quantities. However, the question arises: are relative properties and quantities indeed local?

Keywords: Non-Separability, Entangled States, Physical Symmetries, Bell Inequalities, Special Relativity Theory, Relational Quantum Mechanics

Introduction

Recent papers provide examples of the violation of Bell local realism inequalities (BI) [1] in relativistic experiments. One of the papers describes a thought experiment to measure the life-death correlations of three twins moving in spaceships at different speeds [2]. In another thought experiment, the correlation of the decays of 4 nuclei moving at different speeds is measured [3]. Any entanglement between the objects under consideration is excluded, but calculations still show that with a certain choice of relative velocities BI is violated. These findings may help to present the problem of the relativity of measurable quantities in a broader aspect, not concentrating on explaining quantum mechanics (QM) alone, as is done in Relational quantum mechanics (RQM) [4,5] but considering physics as a whole, since in our opinion physics can be based only on uniform principles.

If we talk about decaying nuclei, it should be noted that the dependence of the correlation of the decays of nuclei A and B on the choice of relative velocity is mathematically rather close to the dependence of the correlation of photon polarizations in entangled pairs on the mutual angles between the axes of the sensors and is determined by the metric of spaces: positive in the case of 3-dimensional space and pseudo-Euclidean in the case of SRT. For the spins of fermions, it is necessary to make a correction that takes into account the ratio of relative angles between the axes of sensors and the angles between the corresponding state vectors in Hilbert space, which is different, but this does not fundamentally change the matter: both quantities are dichotomous in multidimensional space. However, does the similarity of the mathematical description indicate the similarity of the physical mechanisms of BIs violation in SRT and QM?

Experiments with Violation of BI in SRT

For better understanding, consider four-dimensional experiments with decaying nuclei moving at different speeds, as was described in [3] and their parallelism with quantum mechanics. There is a certain parallel between the way measurements are made in the proper relativistic RF on the one hand and the proper settings of a quantum measuring device on the other. For any nucleus, there is always at least one canonical RF in which it can be said with absolute certainty after measuring whether it has decayed or not. In all other RFs, the answer to the question depends on the mutual velocities and distances from the chosen reference body. Similarly, for any quantum system, there is always at least

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one measurement setting in which it is possible to speak with absolute certainty about the result of measuring. For example, for single-photon pure polarized states, it is always possible to choose the direction of the detector axis so that all photons in this state are always detected with certain polarization [6]. In a different setting, there is no exact knowledge on the measurement results, and we can only talk about the probability of 'horizontal' or 'vertical' polarization. Another example: if a particle φ is in the volume V, then the setting when it's registered at any point of V is the proper setting with respect to φ. In any different setting one gets only probability of detection. Just as in SRT for any massive body it is possible to find its proper RF at proper time τ, for any quantum system it is possible to find its proper setting of detectors at certain time t.

The next parallelism consists in the fact that measurements of some quantities in SRT, as well as in QM, can be made only in non-separable systems. In special relativity, this is due to the fact that the velocities are always relative, and only the relative velocities of the pairs of bodies make sense completely independent of the actions of the experimenter. Other fundamental features should be discussed in a similar way. For example, with regard to the polarization of photons and the spins of fermions, only the relative spins and relative polarizations of particles in the pair have an objective physical meaning. It makes sense to talk about non-relative local values only after choosing the measurement settings, and only in the case when the proper setting was chosen will the measurement reliably reflect the relative values. In the case of entangled photon pairs in the singlet state, the measurement setting is proper when the axes of the detectors of observers A and B are parallel to each other or orthogonal to each other [7]. Only then will the measurement of the relative direction of the two polarizations correspond to reality in each measurement.

This means that, in practice, experimenters A and B must align the axes of their sensors, and maintain the established relative direction of the axes throughout the experiment. In the case of relativistic experiments with random events, experimenters must establish the appropriate relative velocities of the systems being measured. Obviously, in both cases, they will have to exchange classical signals before the nonlocal correlation experiment can be carried out at all. Thus, in QM, to the same extent as in SRT, it is only with great difficulty the observed non-classical effects can be attributed to "nonlocality". It turns out that the manifestation of "nonlocality" can be noted only with a reliable channel for the exchange of reliable classical information between experimenters. The situation is reminiscent of quantum teleportation experiments, especially the quantum teleportation experiment to the past [17], where the registration of nonlocal effects is also impossible without maintaining the exchange of classical signals. Such inevitability of the exchange of classical signals in experiments with nonlocality means that the entire range of possible experimental outcomes is physically established at the moment of alignment of the axes of the sensors (in the case of experiments with photon polarization) and at the moment of alignment of relative velocities (in the case of relativistic experiments with random events).

Clarification of the Cause of Violations

However, the noted parallelism between measurements in QM and SRT is insufficient to indicate the reason for the violation of BI in both cases. Perhaps the point is that inferring BI from the logical product of known physical requirements, including locality, property realism, and statistical independence of experimenters, does not allow us to clearly identify one common cause of the violation. It would be a different matter if equivalent inequalities were deduced from a single statement. It could then be argued that the violation of inequality with necessity leads to the violation of this requirement. Speaking of theories that satisfy the principle of relativity of measured quantities (RMQ), it is impossible not to notice that some mathematical sets in them are defined relatively. For example, the sets of experimental results may be described relatively for two massive bodies or two quantum states. At the same time, in canonical set theory, the determining property of the set is defined absolutely. In this case, the property A, on the basis of which a conclusion is made about the belonging of element i to the set α, can be considered an absolute dichotomous quantity A with the values of a_i=±1. Is it possible to derive BI from the absoluteness of sets? In this case, the violation of the obtained inequality would reflect the relativistic nature of the measured quantities.

Derivation of BI from the formulas of canonical set theory

Set absoluteness is reflected in the inclusion-exclusion formula:

$$|A \cup B| = |A| + |B| - |A \cap B| \tag{1}$$

A module sign indicates the number of elements of a finite set.

However, theoretically, property $\mathscr{A}$ can be defined relatively to property $\mathscr{X}$, and property $\mathscr{B}$ can be defined relatively to $\mathscr{Y}$. In this case equation (5.1) does not hold because it assumes that *A* and *B* are unique. That is, when instead of $|A|+|B|-|A \cap B|$ appears $|A_X|+|B_Y|-|A_X \cap B_Y|$ there cannot be a singular $|A \cup B|$.

The considered equality for sets (5.1) in probability theory corresponds to the Lagrange formula, which is valid within the framework of Kolmogorovian axiomatics but is broken in some situations [8]. Let's write it down for random events A_1 and B_1:

$$P(A_1 + B_1) = P(A_1) + P(B_1) - P(A_1B_1) - P(A_1B_1), \tag{2}$$

where the probability of the sum (A_1+B_1) means the probability that either event A_1 or B_1, or A_1 & B_1 occurred.

Since $P(A_1+B_1)$ is a probability, (5.2) implies

$$P(A_1) = P(B_1) - P(A_1B_1) \leq 1. \tag{3}$$

Let us add to the list of conditions for deriving the inequalities the Bayesian formula for the conditional probabilities *P(X|Y)* and *P(Y|X)*, and the joint probability *P(XY)*, as follows:

$$P(XY) = P(X)P(Y \mid X) = P(Y)P(X \mid Y). \tag{4}$$

In (5.4) P(Y|X) =P(Y) and P(X|Y) =P(X) means the statistical independence (factorizability) of two random variables:

$$P(XY) = P(X)P(Y) \tag{5}$$

However, statistical independence is not a requirement for deriving the inequalities sought. On the contrary, Bayes' formula generally assumes the dependence of one random variable on another, because if condition (5.5) is not met, the two random variables *X* and *Y* cannot be called independent. However, the inequality (5.3) remains valid when the two positive terms are multiplied by the conditional probabilities $P(B_0|A_1)$ and $P(A_0|B_1)$:

$$P(A_1)P(B_0 \mid A_1) + (B_1)P(A_0 \mid B_1) - P(A_1 \mid B_1) \le 1 \quad (6)$$

From (5.4) and (5.6) one gets

$$P(A_0 \mid B_1) + P(A_0 \mid B_1) \le 1 + P(A_1 \mid B_1) \quad (7)$$

Let's write (5.7) for the probabilities of correlated measurements, that is, for the probabilities P^cor (a_i,b_j) of such pairs of measurements (a_i,b_j) for which the values of the measured dichotomous quantities A and B coincide (a_i=b_j):

$$P^{cor}(A_0 \mid B_1) + P^{cor}(A_0 \mid B_1) \le 1 + P^{cor}(A_1 \mid B_1) \quad (8)$$

For the obtained averages $\langle XY \rangle$, when the dichotomous quantities X and Y take the values ±1, their expression in terms of the correlation probability is as follows:

$$\langle XY \rangle = P(X^+Y^+) + P(X^-Y^-) - P(X^+Y^-) - P(X^-Y^+) = P^{cor}(XY) - P^{cor}(XY) \quad (9)$$

Now, multiplying the inequality (5.8) by 2 and subtracting 2 from it, one gets the 4-axis inequality for the three averages:

$$\langle A_1 B_0 \rangle + \langle A_0 B_1 \rangle \le 1 + \langle A_1 B_1 \rangle \quad (10)$$

The inequalities (5.8) and (5.10) can be called Absoluteness inequalities (AI), given their origin in the absoluteness of the definitions of standard set theory.

(5.10) implies

$$\langle A_0 B_0 \rangle + \langle A_1 B_0 \rangle + \langle A_0 B_1 \rangle - \langle A_1 B_1 \rangle \le 2 \quad (11)$$

Inequality (5.11) can also be derived from BI-CHSH. Like BI-CHSH, it is violated in QM and SRT. BI-CHSH and AI can be deduced independently from different sets of premises Π_1 and Π_2, so that $(\prod_1 \Rightarrow BI_{CHSH} \Rightarrow (5.11)) V (\prod_2 \Rightarrow AI \Rightarrow (5.11))$. According to de Morgan's rule, in case of violation (5.11), BI-CHSH and AI are refuted together. It also jointly refutes sets of premises of both AI and BI-CHSH: $\neg(5.11) \Rightarrow (\neg \mathrm{BI}_{\mathrm{CHSH}} \wedge \neg \mathrm{AI}) \Rightarrow (\neg \ddot{I}_1 \wedge \neg \ddot{I}_2)$, but since there is only one significant premise for AI inference — the absoluteness of sets — it is always violated when violated (5.11). Thus, regardless of whether any of the three acts — nonlocality [9, 10], superposition [11], or superdeterminism [12] — the relativity of sets always holds in the case of (5.11) violation. On the contrary, nonlocality, superposition, superdeterminism, considerate separately, are not necessary conditions for BI violation.

BI violation and relativity of quantities

In the experiment with four decaying nuclei described here [3], the apparent nonlocality is explained as follows: due to a change in the relative velocity, the value of the relative quantity (mutual state of decay) changes instantaneously. Thus, the relativity of mutual velocities leads to the non-separability of a system of two nuclei, and non-separability leads to an instantaneous correlation between the relative states of decay. It should be noted, that the superluminal correlations do not contradict SRT, because there is no need for any asymmetric signal transfer for (symmetric) correlation [3].

We can also speak about the uncertainty of the properties of a physical system up to the moment of measurement: until this moment, the experimenters in A and B will still have the possibility of a unilateral local change in the relative velocity of the two nuclei. It turns out that until the very moment of measurement, we cannot talk about a definite value of the relative state of decay. The situation fully corresponds to the collapse of the state vector |ψ>, which in the limiting case of an infinite-dimensional Hilbert space means that the state vector normalized to 1 rotates from its previous position and lies exactly on the basis vector $|\psi>_i$ of one of the axes b_i of some infinite-dimensional basis B^j. Alternatively, this can be described as a rotation of the infinite-dimensional basis B^j with respect to the state vector |ψ> with the same result. The established normalization of the vector |ψ> to 1 means that at any moment in the evolution of the system it has exact value of relative property (an exact value with probability 1), but each time this exact value may be existing in a different measurement basis. That is, the difference from the classical system is not that the values of a property are always probabilistic, but that they are always reliable on a different basis. If we could in practice adjust the measuring instrument on a measurement in its own basis B^j we would always reliably obtain some exact value of x_i, where |<ψ_i ┃ ψ_i >|=1. In this sense, QM describes the measurement results deterministically, but imposes certain requirements on the settings of the measuring tool.

In practice, we can implement the required settings only with a small dimension Hilbert space. Thus, we can always choose such a setting B^j of the axes of polarization sensors that the dichotomous polarization state $|\psi>=a_V\ |\psi_V>+a_H\ |\psi_H>$ will be measured with the result "vertically". However, as the number of the Hilbert space dimensions increases, the setting the measuring instrument in the selected basis B^j for an arbitrary state$|\psi>=\sum_{(i=1)}^{N} a_i\ |\psi_i>$ is becoming an increasingly difficult task. This is explained by the fact that with an increase in their number, the axes of the basis become more and more "cramped" on the surface of the (N-1)-dimensional unit hypersphere in Hilbert space. It is increasingly difficult for the experimenter to accurately set the necessary measurement basis. For example, for qubit states, at N = 2, the positive directions of the complex axes are cut off by 1/2N=1/4 part of the 1-dimensional hypersphere ("circle" in Hilbert 2-dim space). At N = 3, this value will decrease and become equal to 1/8. With N>>1, we can't basically set up our measuring device so, that the measurement results become completely predictable. But the accuracy of the device's installation does not have fundamental limitations, such as the Heisenberg uncertainty relation, thus we must exclude the factor of technical perfection of our devices, and proceed from the fact that in some basis the value of the quantum property will be determined accurately even before the measurement collapse.

Thus, a measurement collapse is just a spasmodic change in the basis in which the value of the quantity is accurate. The evolution of the basis nevertheless remains unitary, but the question of why smooth evolution becomes undifferentiable at the moment of measurement remains valid. Perhaps because in physics, as in any natural discipline, we can only describe the results of research with reliable facts. At the same time, it is quite clear that having received information that a certain property A has been accurately measured, we must attribute to this measurement the real time of its implementation, and not the time of our receipt of information about it, otherwise the further evolution of the system (again smooth) will be calculated by us with errors. Thus, if we proceed from the considerations of the correctness of the predictions, there is not an ounce of subjectivity left in the measurement collapse.

If we take a closer look at another well-known problem – the instantaneous propagation of the single-particle state collapse – we can see that the "instantaneous" nature of such a collapse is also explainable from the point of view of the objectivist approach. The state vector of such a particle is an objective reality in the sense that its norm is always equal to 1, regardless of the choice of the measuring basis. At the same time, the distribution of probabilities of finding a particle in all possible coordinates is subject-dependent, since it depends on the choice of a measuring basis. Of course, there can be no physical restrictions on the propagation speed for a particle subject-dependent property. How a particle can "know" where it will be registered is another question related to the relativity of physical quantities. The number of N particles (in the case of single-particle state n=1) is a relative quantity too. Thus, the statement about the "presence" of a particle in the point x_i does not have a physical meaning in general, but only in relation to the "absence" of a particle in other points. Thus, in the view of experiments with the collapse of single-particle states, the assumption of spooky action at distance is redundant too.

Returning to relativistic experiments with decaying nuclei, it should be noted that the window for BI violation opens when the number of nuclei is 3 or more. Since the nuclei A and B are in the same position, the measured value of the relative dichotomous quantity (the correlation of decay in this case) does not depend on its measurement in A or B. However, for three or more nuclei, the situation changes. Since the relative quantity can only be defined for two nuclei, there is no definitive way to determine it for three or more nuclei. For example, if, according to measurements made in their proper RF, the decay states of nuclei A and B are correlated, B and C are correlated, and A and C are anticorrelated, then we cannot define a distribution of the measured quantity that is common to all three nuclei [13]. The absence of a single set of property values in each three-measurement experiment will lead to the absence of a probability distribution when the experiment is repeated. Thus, BIs will be broken.

The situation is clarified by the following Gedankenexperiment. To begin with, let's look at the expression on the basis of which BI-CHSH is usually derived [14]:

$$s_i = a_i\left(b_i + b_i^{'}\right) + a_i^{'}\left(b_i - b_i^{'}\right) = a_i b_i + a_i b_i^{'} + a_i^{'} b_i - a_i^{'} b_i^{'} \tag{12}$$

where $a_i^{(')}, b_i^{(')} = \pm 1$ are the values of dichotomous random variables are obtained as a result of 4 measurements, combined in this case in one four-dimensional with index i. s_i can only have two values: +2 and –2, since one expression in parentheses is always 0, hence $|s_i|=2$. After moving to the averages $\langle a_i^{(')}, b_i^{(')} \rangle$ BI-CHSH is gotten:

$$S = |\langle a_i b_i \rangle + \langle a_i b_i^{'} \rangle + \langle a_i^{'} b_i \rangle - \langle a_i^{'} b_i^{'} \rangle| \le 2. \tag{13}$$

However, the form of possible dependence and its physical causes are not limited. In addition to non-local action, this can be, for example, a local change in the velocity of one body, leading to an instantaneous change in the value of some relative quantity, for example, relative velocity.

Suppose that in a measurement experiment the sign of the relative velocity of two laboratories, *A* and *B,* is measured. Two experimenters in *A* and *B* can independently select two coordinate velocities of their laboratory in some common $RF: v_{A'}, v_A^{'}, v_B, v_B^{'}$. If, as a result of the choice made, the relative velocity of the two laboratories along the X-axis is negative (the laboratories are approaching each other), we will assume that the values a and b of some dichotomous quantity Σ have been measured with the same sign. Then it is written either a = 1 and b = 1, or a = −1 and b = −1. If the relative velocity is positive (the laboratories are moving away from each other), the values of a and b have been measured with opposite signs. Then it is written either a = 1 and b = −1, or a = −1 and b = 1. The product ab gives us the correlation function $\langle ab \rangle = ab.$ Let's conduct an experiment to measure $a^{(')}\ and\ b^{(')}$ in 4 paired measurements $a_b b_a, a_{b'} b_a^{'}, a_b^{'} b_{a'}, a_{b'}^{'} b_{a'}^{'}$ with subsequent calculation of the correlation function: $a_b b_a = a_b b_a, a_{b'} b_a^{'} = a_{b'} b_a^{'}, a_b^{'} b_{a'} = a_b^{'} b_{a'}, a_{b'}^{'} b_{a'}^{'} = a_{b'}^{'} b_{a'}^{'}$. When choosing $\boldsymbol{v}_A = 0\frac{\hat{e}\grave{i}}{\div}, \boldsymbol{v}_A^{'} = 20\frac{\hat{e}\grave{i}}{\div}, \boldsymbol{v}_B = 10\frac{\hat{e}\grave{i}}{\div}, \boldsymbol{v}_B^{'} = 10\frac{\hat{e}\grave{i}}{\div}$ the result of the quantity Σ measurement $a_b = 1, b_a = 1, a_{b'} = 1, b_a^{'} = 1, a_b^{'} = 1, b_{a'} = 1, a_{b'}^{'} = 1, b_{a'}^{'} = -1$. Thus, one gets $|2s| = \left|a_b b_a + a_{b'} b_a^{'} + a_b^{'} b_{a'} - a_{b'}^{'} b_{a'}^{'}\right| = 4 > 2$. It means that BI is broken in a series of one experiment. Of course, the inequality will also be violated by repeating similar measurements with the preservation of the mutual velocity settings with some degree of accuracy and taking the averages of $a^{((')}$ $b^{((')}$. It is worth noting that Σ is a dichotomous quantity, so the measurement gives us a minimal amount of information of 1 bit like measurements in QM. Obviously, a violation of BI does not contradict the presence of hidden variables [15,16] if they are represented by relative quantities. However, the question remains: could relative properties and quantities be regarded as truly local?

Obviously, the answer to this question is no. The subjectivity of the reference systems choice leads to the fact that only the relative properties of physical systems, described by two-place predicates like P(A,B)=ρ, have a fundamental physical significance. These can be real, or complex numbers, or operators. It is clear that a physical theory built on the basis of the description of physical properties by two-place predicates cannot, in principle, be transformed into a local theory based on one-place predicates, such as P(A)=ρ. This simple conclusion has far-reaching consequences in the form of the fundamental incompatibility of such theories as QM and General Relativity.

The issue of united approach to the problem of measurement for all physics is also methodologically relevant. At present, the illusion is created that this problem exists only in quantum mechanics. But in order to assess the significance of this problem for other branches of physics, it is necessary to make sure that the method of measurement is common to all physics, which is obviously not the case at present. For example, in quantum mechanics, the measurement of probability must take place in a sufficiently large series of homogeneous experiments, which is fully consistent with the mathematical definition of probability. Probability in this case is always defined in the context of a certain measurement procedure. As a result, no matter how low the pretest probability is, after a measurement collapse it is always equal to 1. However, in other fields, such as cosmology, for example, here [18], or thermodynamics [19], the requirement to measure probability in a series of homogeneous experiments is simply ignored, the procedure for probabilities measuring is not described in any way. As a result, there is bewilderment about the allegedly extremely unlikely anomalies. At the same time, it is forgotten that the probability is always pre-test, the series of test experiments must be homogeneous, and it is not correct in principle to talk about any other probability than equal to 1 after some phenomenon has already been detected. These examples show how important is to systematize and refine measurement procedures in all areas of physics without exception, and quantum mechanics is essentially the "gold standard" in this regard.

Conclusion

According to Heraclitean view on the causality, there is a cause for everything in the world. Thus $\forall B \exists A : B \Rightarrow A$ where $B \Rightarrow A$ means that $\neg(B \wedge \neg A)$. In this case, A is a set of causes leading to B. With this understanding, the 'cause A of something B' is a prerequisite. At the same time, B is understood in general as any statement or negation, since the connection between necessary and sufficient conditions is in itself a necessary condition for successful scientific communication. The epistemological success of the language of cause and effect is naturally correlated with the presence of causal relationships in physical ontology, since the only thing physicists do is create and analyze messages addressed to each other. For similar reasons, the need for the subject independence (objectivism) is closely related to the self-determination of the boundaries of physics as a science that studies things that do not depend on the arbitrary choice of their descriptions. Necessity is the absence of arbitrary choice. Therefore, the principle of subjective independence (SI) is a natural necessary condition for the physical description and then for the discussed physical reality. No less important for physics is the requirement for an initial agnostic position: after all, physicists should not invent experimental facts. This necessity can be formulated as a requirement of the principle of a priori maximum possible ignorance (AMPI).

Since these two fundamental requirements are only necessary but not sufficient conditions for productive physical discourse, it is impossible to deduce forms of physical description from them. On the contrary, the forms of physical description should imply the implementation of SI and AMPI. For example, for a three-dimensional space, the subjective independence of relative angle measurements follows from isotropy. For the four-dimensional space-time of SRT, objectivity of relative velocities follows from the equality of the canonical RFs. For Hilbert spaces of QM, the objectivity of quantum correlations follows from the equality of measurement bases. The requirement of AMPI follows from the equality of the axes of Hilbert space basis.

In parallel, the symmetry of spaces implies the relativity of distances, relative angles, and relative scales. Only relative magnitudes turn out to be subject independent in spaces, and in this sense, they are undoubtful physical quantities. Thus, the relativity of physical quantities is not a problem but a remedy. As shown above, the relativity of measurable quantities described in theories based on spaces leads to the fact that BIs can be violated. Then the phenomenon of violation itself is a marker of correlation between our requirements for description and the theories that we construct, taking into account these requirements and experimental data. On the one hand, if a theory does not meet the requirements of physics as a subject, it is not physical. On the other hand, if we were not able to find objects whose descriptions fit the principles of physics that we believe a priori, we would probably have to relax our requirements in order to expand the boundaries of what is possible. Still, SI and AMPI seem too fundamental to be abandoned without the risk of chaos. If the conclusions of this study are correct, the violation of BIs not only does not lead to subjectivism, but, on the contrary, confirms the subject-independent nature of physics.

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