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Nonlocality and nonseparability of quantum and relativistic systems

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Abstract. The concept of nonlocality and its role in the violation of Bell's inequalities are discussed. A weaker nonlocality is revealed in comparison with Albert Einstein's "Spooky Action at a Distance" and at the same time does not contradict the principles of the special theory of relativity (STR). A correlation statistical experiment with the violation of the Clauser–Horne–Shimony–Holt inequality in STR is described, in which weak nonlocality is manifested. The correlation in such an experiment propagates with infinite speed in the proper frame of reference of the measuring device.

Keywords: Bell's inequalities, nonlocality, special relativity, Spooky Action at a Distance, entangled states

1. Introduction

Despite the unprecedented practical success of quantum mechanics (QM) and the 'second quantum revolution' that continues at an increasing rate, no generally accepted explanation for quantum effects has yet been found. On the contrary, attempts to provide an 'unconventional' explanation of quantum reality by invoking the idea of retrocausality, asserting 'superdeterminism,' and rejecting a single objective reality are proliferating. Meanwhile, the enormous influence of quantum mechanics on the entire spectrum of scientific disciplines demands a clear understanding of quantum phenomena. The awarding of the 2022 Nobel Prize for the experimental confirmation of the paradoxical nature of quantum mechanics does not absolve us from the obligation of striving to rid physics of the inexplicability and controversial nature of theories and their interpretations.

In a recently published review [1] dedicated to the 2022 Nobel laureates in physics, the authors raised an important and fundamental question for all of physics: how should we understand quantum mechanics? It may seem strange to nonphysicists that one of the most successful physical theories remains full of mysteries and continues to spark debate. This is all the stranger given the enormous influence the emergence of quantum mechanics has had not only on the scientific paradigm but also on the realm of scientistic philosophical constructions. However, attempting to base a worldview on something whose stability and immutability are uncertain appears extremely risky.

Among other issues, review [1] describes an attempt to explain a number of the most paradoxical quantum effects by invoking the idea of retrocausality and constructing an expanded formalism of quantum theory on its basis. While the unusualness and mathematical beauty of this method must be acknowledged, a legitimate question arises: is the idea of retrocausality truly indispensable in quantum mechanics? Or can more conservative assumptions be used to explain quantum effects? Quantum nonlocality raises a similar question: should we really consider it 'mysterious action at a distance,' or is a weaker assumption, compatible with special theory of relativity (STR), sufficient to explain the relevant effects, e.g. [1–7]?

Analysis of violations of Bell's inequalities (BI) [8–10] once led to an unequivocal refutation of local realism in quantum mechanics. However, there are two possible causes for the violations here: nonlocality and/or quantum superposition. From other experiments, e.g. [11, 12], it follows that, most likely, both hold. John Bell [8] derived his inequalities from two premises: the reality of the existence of values of quantities observed before measurement, and the independence of measurement from the settings of a distant detector. Literally: "*the result of the measurements of one system be unaffected by operations on a distant system with which it has interacted in the past*." Superposition, if understood as the absence of a measured property before measurement, negates the first premise, and nonlocality negates the second.

At the same time, other, less obvious, conditions for the observance of Bell's inequalities cannot be ruled out. For example, the actions of experimenters and the operation of detectors must not be somehow correlated under the influence of past interactions. It is also implied that the existence of values of measured properties must remain objective, in the

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sense that there should not be a situation in which one experimenter obtains one thing, and another something else. It should also not be the case that the existence or absence of a property value depends on actions 'on paper,' for example, on the choice of one of the equivalent reference frames (RFs).

2. Bell's inequality in the Clauser–Horne–Shimony–Holt form

We briefly recall the derivation of the Bell's inequality in the Clauser–Horne–Shimony–Holt (CHSH) form [14–16], with emphasis appropriate to our situation. In the simplest case [10, 17], the arithmetic formula $s_i = a_i(b_i + b_i') + a_i'(b_i - b_i')$ is taken, where $a_i^{(\prime)}, b_i^{(\prime)} = \pm 1$ are the values of dichotomous random variables obtained by four measurements, combined in this case into a single 'four-dimensional' measurement labelled by index i. The quantity s_i can take only two values: $+2$ and -2, since one of the expressions in parentheses will always be zero, which implies the equality $|s_i| = 2$, and, taking into account multiplication by probabilities to obtain average values, inequality $\langle |s_i| \rangle \leqslant 2$ follows from it.

It is important to emphasize that the four quantities a_i, a_i', b_i, b_i' must be described by four-dimensional conditional probabilities [13]. Thus, inequality $\langle |s_i| \rangle \leqslant 2$, in order to maintain its universal validity, implicitly requires the coexistence of values in each four-dimensional measurement. If the number of obtained values is greater than four, which can happen in the case of a certain functional dependence of the observed values on each other, then the inequality is violated. In fact, this means a transition from a description within the framework of four-dimensional conditional probabilities to a higher dimension, up to eight-dimensional [20].

Thus, the physical requirements of locality and realism can be sufficient grounds for deriving the inequality considered. And, according to De Morgan's well-known logical rule, the denial of the inequality implies either the denial of locality, or realism, or both. On this basis, in physics discourse, it is common to speak of a violation of local realism as the 'physical cause' of the violation of the corresponding inequalities, although a violation of local realism does not logically imply a violation of the inequalities, but rather the opposite: a violation of the inequalities implies a violation of locality, or realism, or both.

If the described four-dimensional measurement is repeated a sufficiently large number of times, $N \gg 1$, the following inequality will hold:

$$S_i = \left|\sum_{i=1}^{N} s_i\right| = \left|\sum_{i=1}^{N} \left[a_i b_i + a_i b_i' + a_i' b_i - a_i' b_i'\right]\right| \leqslant 2N\,. \quad (2.1)$$

Let us denote the variants of correlation of values in each component of inequality (2.1) by $(++)$, $(--)$, $(+-)$, and $(-+)$, and the number of occurrences of any variant in a series of N joint measurements for the values $a_i^{(\prime)}$ and $b_i^{(\prime)}$ ($a_i^{(\prime)}$, $b_i^{(\prime)} \in \{-1, +1\}$) of the pair of random variables $A^{(\prime)}$ and $B^{(\prime)}$ by $n^{++}_{a^{(\prime)}b^{(\prime)}}, n^{--}_{a^{(\prime)}b^{(\prime)}}, n^{+-}_{a^{(\prime)}b^{(\prime)}}$, $n^{-+}_{a^{(\prime)}b^{(\prime)}}$. Then $n^{++}_{a^{(\prime)}b^{(\prime)}} + n^{--}_{a^{(\prime)}b^{(\prime)}} + n^{+-}_{a^{(\prime)}b^{(\prime)}} + n^{-+}_{a^{(\prime)}b^{(\prime)}} = N$. Let us denote the number of correlations and the number of anticorrelations for the values of the pair of random variables $A^{(\prime)}$ and $B^{(\prime)}$ obtained during the measurement as

$$N^{\rm cor}_{a^{(\prime)}b^{(\prime)}} \stackrel{\rm def}{=} n^{++}_{a^{(\prime)}b^{(\prime)}} + n^{--}_{a^{(\prime)}b^{(\prime)}}\,, \quad N^{\rm ant}_{a^{(\prime)}b^{(\prime)}} \stackrel{\rm def}{=} n^{+-}_{a^{(\prime)}b^{(\prime)}} + n^{-+}_{a^{(\prime)}b^{(\prime)}}\,.$$

We define the correlation function (moment) of a representative sample with a sufficiently large N for the pair of random variables $A^{(\prime)}$ and $B^{(\prime)}$ as

$$\left\langle A^{(\prime)} B^{(\prime)} \right\rangle \stackrel{\rm def}{=} \frac{\left(N^{\rm cor}_{a^{(\prime)}b^{(\prime)}} - N^{\rm ant}_{a^{(\prime)}b^{(\prime)}}\right)}{N} = P^{\rm cor}_{A^{(\prime)}B^{(\prime)}} - P^{\rm ant}_{A^{(\prime)}B^{(\prime)}}\,.$$

Since for correlating pairs the product $a_i^{(\prime)} b_i^{(\prime)}$ is always positive and equal to 1 and for anticorrelating pairs it is always equal to -1, $\langle A^{(\prime)} B^{(\prime)} \rangle = \left(\sum_{i=1}^{N} a_i^{(\prime)} b_i^{(\prime)}\right)/N$ and the inequality (2.1) takes the CHSH form:

$$\begin{aligned} &\left|\langle AB \rangle + \langle AB' \rangle + \langle A'B \rangle - \langle A'B' \rangle\right| \\ &= \left| \frac{\left(\sum_{i=1}^{N} a_i b_i\right)}{N} + \frac{\left(\sum_{i=1}^{N} a_i b_i'\right)}{N} + \frac{\left(\sum_{i=1}^{N} a_i' b_i\right)}{N} \right. \\ &\quad \left. - \frac{\left(\sum_{i=1}^{N} a_i' b_i'\right)}{N} \right| \leqslant 2\,. \end{aligned} \quad (2.2)$$

It can be derived also exclusively from the existence of four-dimensional classical probability distributions without additional assumptions [13].

In some cases, the equivalent inequality for probabilities turns out to be more convenient. Since for large enough N $P^{\rm cor}_{A^{(\prime)}B^{(\prime)}} = N^{\rm cor}_{a^{(\prime)}b^{(\prime)}}/N$ and $P^{\rm ant}_{A^{(\prime)}B^{(\prime)}} = N^{\rm ant}_{a^{(\prime)}b^{(\prime)}}/N$, we have $\langle A^{(\prime)} B^{(\prime)} \rangle = P^{\rm cor}_{A^{(\prime)}B^{(\prime)}} - P^{\rm ant}_{A^{(\prime)}B^{(\prime)}} = 2P^{\rm cor}_{A^{(\prime)}B^{(\prime)}} - 1$, and (2.2) can be rewritten as

$$0 \leqslant P^{\rm cor}_{AB} + P^{\rm cor}_{AB'} + P^{\rm cor}_{A'B} - P^{\rm cor}_{A'B'} \leqslant 2\,. \quad (2.3)$$

The inequalities are derived from the coexistence of values in each four-dimensional measurement. Physically, this means that they existed independently of the measurement events, and therefore even before such measurements, since in experiments with entangled particle pairs, measurements are not performed simultaneously. The point is that the primed and unprimed observables in real experiments correspond to different rotation angles of the polarization analyzers, which cannot take two different values at once. In other words, an actual measurement carries information about only two of the four quantities: one of each of the pairs (a_i, a_i') and (b_i, b_i').

The coexistence of values in each four-dimensional measurement is usually called 'property realism' (PR). The absence of influence of result A on result B means their locality (L). Therefore, it can be argued that Bell's inequalities in the CHSH form (BI–CHSH) follow from 'property realism' and locality: (PR $\wedge$ L) $\Rightarrow$ BI–CHSH. In this case, according to De Morgan's rule, a violation of the inequalities leads either to a violation of 'property realism,' or to a violation of locality, or to both: $\neg$BI–CHSH $\Rightarrow$($\neg$PR $\vee$ $\neg$ L). Thus, if for some objective reasons the requirement of 'property realism' cannot be met in a physical theory, this is enough to explain the results of physical experiments with violation of inequalities, and there is no need to seek an explanation in nonlocality. A place for nonlocality will be found when its mechanisms are clearly explained in the theory. It should not be postulated as some kind of 'mysterious action,' although it manifests itself in the reduction of the wave function during measurement. But is such a reduction an action? Hardly, because it can be superluminal, and superluminal force action, according to the special theory of relativity, is impossible. And what about information impact? On the one hand, the transfer of information at superluminal speed is also impossible according to the no-communication theorem [18]. On the other hand, the wave function reduction can be rather quick in an entangled pair of particles. But what is the status of the wave function existence? Objective or purely calculational? And if the role of the wave function is reduced to only a computational technique, like a slide rule, then does such nonlocality exist at all? Let us consider a simple example. If measuring the energy, or momentum, or angular momentum of one of the particles entangled with respect to these parameters yields a statistical result, unknown in advance, then the result of measurement for the second particle is predetermined and uniquely depends on that of the first measurement. How did the second particle 'recognize' it, being far away and not communicating with the first particle via any known types of interaction? Clearly, the whole point is to observe conservation laws, which, in turn, follow from the homogeneity and isotropy of spacetime, as implied by Emmy Noether's theorem [19]. Thus, it is spacetime itself that is responsible for quantum nonlocality, the existence of which should also be beyond doubt [21].

3. An example of the violation of Bell's inequalities in the Clauser–Horne–Shimony–Holt form in special relativity

A recent paper [26] demonstrated, using a specific example, the possibility of violating BI–CHSH in a purely classical relativistic case. However, the journal's format did not allow us to substantiate this result in detail and analyze its causes. Here, we will consider another gedanken experiment with four separated radioactive nuclei. Let us denote these nuclei by R_1, R_2, R_3, R_4. According to the law of radioactive decay, $\mathrm{d}N/\mathrm{d}t = -kN$, where N is the number of nuclei, $\mathrm{d}N$ is the number of decays, and k is the probability of decay per unit time (decay rate). The time dependence of the number of decaying nuclei is exponential, but in our gedanken experiment, for simplicity, we will assume this dependence to be linear over a short time interval. While the choice of four decaying nuclei as a stochastic system is purely illustrative, it is not difficult to come up with other examples where the dependence of the number of random events on time is strictly linear.

Thus, the probability $P(A_{jj})$ of the decay of a nucleus R_j over a time interval Δt_{jj}, measured in the proper canonical reference frame S_j of the nucleus R_j, is $P(A_{jj}) = k\Delta t_{jj}$. Let us denote by A_{ij} the state of a nucleus at rest in the reference frame S_i, measured in the reference frame S_j. The left subscript here indicates the nucleus, and the right one indicates the reference frame in which time is measured.

According to accepted terminology, canonical reference frames are those in which the reference bodies move without acceleration, and a proper reference frame for body B is one in which the velocity of this body is zero. Since motion in special relativity is relative, and all canonical reference frames are equivalent, we have to choose which of the two frames of reference to consider 'at rest' and which to consider 'moving.' If we define reference frame S_i as 'moving' and S_j as 'at rest,' then a clock for which the moving reference frame S_i is proper will, as a result of relativistic time dilation, lag behind the clock for which S_j is proper:

$$\Delta t_{ij} = \frac{\Delta t_{ii}}{\gamma_{ij}} = \Delta t_{ii}\sqrt{1 - \frac{v_{ij}^2}{c^2}} \stackrel{\text{def}}{=} \Delta t_{ii}\, r_{ij} \,,$$

where

$$\gamma_{ij} = \frac{1}{\sqrt{1 - v_{ij}^2/c^2}} \stackrel{\text{def}}{=} \frac{1}{r_{ij}}$$

is the relativistic factor, v_{ij} is the velocity of R_i with respect to R_j, Δt_{ii} is the time interval measured by the clock for which the reference frame S_i is proper, Δt_{ij} is the time interval between the same events, but measured by the clock, for which the proper reference frame is S_j. Thus, the left subscript numbers the pairs of time-interval measurement events, and the right subscript numbers the reference frames, in which the time interval between events in a given pair was measured.

By 'measurement in the reference frame S_j' we should generally understand locking of the time and spatial coordinates of the decay state measurement to the coordinate grid of the reference frame S_j. Then, from the point of view of an observer considering S_j as a 'resting' reference frame, the probability $P(A_{ij})$ of measuring the decay state A_{ij} of the nucleus R_i will be γ_{ij} times smaller than the probability $P(A_{ii})$ measured in the proper reference frame S_i of the nucleus:

$$P(A_{ij}) = \frac{P(A_{ii})}{\gamma_{ij}} = P(A_{ii})\sqrt{1 - \frac{v_{ij}^2}{c^2}} \stackrel{\text{def}}{=} r_{ij}\, P(A_{ii}) \,, \qquad (3.1)$$

where $r_{ij} = \sqrt{1 - v_{ij}^2/c^2}$, $0 \leqslant v_{ij} < c$ is the relative velocity, and c is the speed of light in vacuum.

Since in our experiment the number of a nucleus corresponds to the number of its proper reference frame, there is no need to introduce separate indices of nuclei for measurements of their states A_{ij} in different reference frames: the left subscript simultaneously denotes the ordinal number of the nucleus and its proper reference frame. Since nuclei decay independently, then, based on Eqn (3.1), the joint probability $P^{++}(A_{ij}A_{jj})$ of finding atoms R_i and R_j in a decayed state will be equal to the product of local probabilities measured in the reference frame S_j: $P^{++}(A_{ij}A_{jj}) = P(A_{ij})P(A_{jj}) = r_{ij}P(A_{ii})P(A_{jj}) = r_{ij}(k\Delta t_{ii})(k\Delta t_{jj})$. The time intervals Δt_{ii} and Δt_{jj} are measured by identical clocks, each in its own proper reference frame. Identical clocks in their proper reference frames show the same time, and therefore we can omit the proper time indices and rewrite: $\Delta t_{ii} = \Delta t_{jj} \stackrel{\text{def}}{=} \Delta t$, $P^{++}(A_{ij}A_{jj}) = r_{ij}(k\Delta t)^2$.

Since nuclei moving uniformly and rectilinearly with different velocities and their proper reference frames are completely equivalent, we can equally well choose the proper reference frame S_i of another nucleus R_i for measuring probabilities and write: $P^{++}(A_{ii}A_{ji}) = P(A_{ii})P(A_{ji}) = r_{ji}P(A_{ii})P(A_{jj}) = r_{ji}(k\Delta t)^2 = r_{ij}(k\Delta t)^2 = P^{++}(A_{ij}A_{jj})$. Since the result of measuring the joint probabilities does not depend on the choice of one of the two proper reference frames, we can omit the indices indicating the reference frames, writing

$$P^{++}(A_iA_j) = r_{ij}(k\Delta t)^2 \,. \qquad (3.2)$$

Accordingly, the joint probability $P^{--}(A_iA_j)$ of measuring A_i and A_j of nuclei R_i and R_j in the undecayed state will be equal to the product of the probabilities of finding these nuclei in the undecayed state when measuring in one of the two proper reference frames, S_j or S_i:

$$\begin{aligned} P^{--}(A_iA_j) &= P(\overline{A_{ij}})P(\overline{A_{jj}}) = P(\overline{A_{ji}})P(\overline{A_{ii}}) \\ &= \big(1 - P(A_{ij})\big)\big(1 - P(A_{jj})\big) = \big(1 - r_{ij}P(A_{ii})\big)\big(1 - P(A_{jj})\big) \\ &= \big(1 - r_{ij}k\Delta t_{ii}\big)(1 - k\Delta t_{jj}) \,, \qquad (3.2a) \end{aligned}$$

where $P(\overline{A_{ij}})$ is the probability that nucleus R_i is found undecayed when measuring its state in reference frame S_j. The probabilities $P(\overline{A_{jj}}), P(\overline{A_{ji}}), P(\overline{A_{ii}})$ are similar.

We denote pairs of nuclei as correlated when the two nuclei are in similar states, i.e., if one has decayed, then the other has too, and vice versa. The probability of correlation in this case is equal to

$$\begin{aligned} P_{ij}^{\text{cor}} &= P^{++}(A_iA_j) + P^{--}(A_iA_j) \\ &= r_{ij}(k\Delta t)^2 + 1 - k\Delta t - r_{ij}k\Delta t + r_{ij}(k\Delta t)^2 \\ &= 1 - k\Delta t(1 + r_{ij}) + 2r_{ij}(k\Delta t)^2 \,. \end{aligned} \tag{3.2b}$$

The probability of pairwise anticorrelation P_{ij}^{ant} in this case is the probability that two nuclei, R_i and R_j, are in different states: one of them has decayed, and the other has not: $P_{ij}^{\text{ant}} = 1 - P_{ij}^{\text{cor}}$. We define the pairwise correlation function (moment) $\langle A_iA_j\rangle$ for a pair of nuclei as $\langle A_iA_j\rangle \stackrel{\text{def}}{=} P_{ij}^{\text{cor}} - P_{ij}^{\text{ant}}$. Let us calculate the correlation moments of the decay state for four different pairs taken from four nuclei with given relativistic velocities and substitute them into the BI–CHSH: $s = |\langle A_1A_2\rangle + \langle A_2A_3\rangle + \langle A_3A_4\rangle - \langle A_1A_4\rangle| \leqslant 2$.

Let us specify the coordinate velocities of nuclei in the laboratory RF $S_\Lambda \equiv S_2 \equiv S_3$ as follows: $v_1 = -(1/3)c, v_2 = 0, v_3 = 0, v_4 = (1/3)c$. Using the formula for the relativistic addition of velocities [22] $v_{ij} = (v_i + V_{ji})/(1 + v_iV_{ji}/c^2)$, where in our case the velocity of the reference frame is $V_{ji} = -v_j$, we calculate the relative velocities of the atoms: $v_{12} = (1/3)c$, $v_{23} = 0$, $v_{34} = (1/3)c$, $v_{14} = 0.6c$. We calculate the required coefficients using the formula $r_{ij} = [1 - (v_{ij}/c)^2]^{1/2}$. The result is $r_{12} = r_{34} \approx 0.949$, $r_{23} = 1$, $r_{14} \approx 0.632$.

Since for a pair of random variables A_i and A_j $\langle A_iA_j\rangle \stackrel{\text{def}}{=} P_{ij}^{\text{cor}} - P_{ij}^{\text{ant}} = 2P_{ij}^{\text{cor}} - 1$, with (3.2b) taken into account, the moments are equal to

$$\langle A_iA_j\rangle = 2\big(1 - k\Delta t(1 + r_{ij}) + 2r_{ij}(k\Delta t)^2\big) - 1 \,. \tag{3.3}$$

We substitute them into BI–CHSH:

$$s = \big|2 - 4k\Delta t + (r_{12} + r_{23} + r_{34} - r_{14})\big(4(k\Delta t)^2 - 2k\Delta t\big)\big| \,, \tag{3.4}$$

and set $k\Delta t = 0.95$, then we obtain $s \approx 2.073$, with a violation of the BI–CHSH.

One can try to question the purity of the experiment by pointing out that the probabilities are measured in different proper reference frames, and if they are reduced to a single reference frame, the violations disappear. But measuring correlations in different reference frames is completely analogous to measuring quantum correlations in different measurement bases, when the moments $\langle AB\rangle$, $\langle AB'\rangle$, $\langle A'B\rangle$ and $\langle A'B'\rangle$ are measured separately at different rotation angles of the polarization analyzers. Therefore, to keep the experimental logic unified, it is necessary in the relativistic case to act in a manner similar to our actions during quantum measurements.

As is well known, the a priori equality of canonical reference frames is a firmly established fact, from which it follows that preference for one of them can be made only based on physical facts, without any arbitrary choice of the observer. For example, for each body possessing a certain 4-velocity v_{0-3}, there exists a unique privileged reference frame in which the spatial components of the 4-vector v_{0-3} are zero. This privileged reference frame is its proper RF. In this case, the privileged position of its own proper reference frame is determined by the nature of the body's motion and does not depend on subjective choice. Thus, the privileged position of proper reference frames with respect to their reference bodies contradicts neither the principle of a priori equality of canonical frames nor the principle of objectivity. It follows that the only way to avoid subjectivity in our experiment is to use, instead of the coordinate velocities taken in one chosen reference frame, the relative pairwise velocities of the nuclei, i.e., using the proper reference frames of nuclei for calculations. Only the proper reference frames of nuclei, i.e., those in which the velocities of nuclei are zero, are naturally chosen reference frames in the situation. Otherwise, both the relative velocities themselves and the associated results of measuring other quantities become subject-dependent. Unlike coordinate velocities, relative velocities do not depend on the choice of reference frame, and by using them in calculations, we immediately obtain a direct and objective measurement result [23], in the sense that it does not depend on our 'paper' choice, i.e., a choice made 'at the tip of the pen' and not in an actual experiment. We did just that, using the proper reference frames of decaying nuclei for calculations.

The derivation of the inequalities described in Section 2 assumes the simultaneous existence of all four quantities. However, in STR, objective simultaneity does not exist. Therefore, the inequalities can be violated, as we have documented. The absence of objective simultaneity directly leads to the nonseparability of relativistic systems, and therefore to nonlocality, since the system cannot be correctly and unambiguously described otherwise. In more detail: when the velocity of one of the nuclei changes, a parameter related to the entire system changes, namely, the correlation of its state with the states of distant nuclei. Moreover, this change in correlation (and joint probabilities) must propagate in space instantaneously and immediately encompass the system of two nuclei. Otherwise, new local changes will be delayed, and the joint probabilities characterizing the state of the entire system will cease to be defined.

This instantaneous propagation of the correlation does not imply instantaneous unidirectional signal transmission, since it will be noticeable only retrospectively: when comparing local nuclear decay observation logs, the experimenter will see the local times of the decay events, as well as the local time when the nucleus's velocity changed (if this occurred). But what exactly an observer located in the same (proper) reference frame with the nucleus R_i will detect, or what will his instrument record at the moment of the change in the velocity of his laboratory? It will be noticed that the synchronizing signal coming from the source in the laboratory of the nucleus R_j has changed its frequency, which is a sign that the relative velocities of the two laboratories have changed at this instant. Naturally, the lower the carrier frequency of the time synchronization signal, the greater will be the error in measuring the moment of the relativistic system state revision. The error will be of the order of $\pm 1/2\nu$, where ν is the frequency of the synchronizing signal coming from the other laboratory. This circumstance will have to be considered when designing a real experiment; the distances between atoms must be sufficiently large, and the frequency of time synchronization between laboratories must be high enough to minimize the effects of uncertainty in measuring the time of state transitions in an inseparable system.

Since decay correlations make sense for a pair of atoms in which the atoms and their respective reference frames are equivalent, these correlations and their instantaneous changes can be considered equally in either of the two reference frames of a given pair. Thus, 'instantaneous' in this experiment should be understood not as 'generally instantaneous for any reference frame,' but as 'instantaneous for a given pair' (considering the possibility of calculation in either of the two proper reference frames), which does not contradict the a priori relativity of simultaneity in special relativity. In other reference frames, such correlations may be not 'instantaneous' but 'superluminal,' since we are talking about spacelike relativistic intervals between events. The moment of beginning of the relative time dilation due to a change in relative velocity appears only in our calculations.

It should be noted that correlations, whether classical or quantum, can in principle be superluminal, and this does not violate the principles of special relativity. For example, a spot of an electron beam on a zinc sulfide screen in a cathode-ray tube or an ordinary sunbeam on a wall can move at superluminal speed, which is entirely consistent with the principles of special relativity. It is easy to imagine an experiment in which a spot on the Earth's surface, formed by a laser beam emanating from a space satellite, moves across the surface at superluminal speed and, with some probability, causes a fire first at point A and then at point B. If such an experiment is repeated a sufficiently large number of times, we can speak of a superluminal correlation between the fires at points A and B. Moreover, according to special relativity, there will always be a superluminal correlation in which the rate of correlation transfer becomes infinite, i.e., two correlated events occur simultaneously. Naturally, there will be no violation of special relativity.

At the same time, the directed transmission of classical information from point A (source) to point B (receiver), unlike correlation, is always limited by the speed of light. This difference is obviously explained by the fact that correlation, unlike the directed transmission of information, is a process symmetrical in its direction: we cannot single out one direction in which it propagates that would be preserved in all reference frames. Therefore, correlated events can be connected by a space-like interval, the ends of which, depending on the choice of reference frame, can be in direct order, in reverse, or even simultaneous. Unlike negative (space-like) intervals, nonnegative (time-like and light-like) intervals have an unambiguous temporal sequence of the ends of their segments, firmly established for all reference frames. Thus, the unidirectional transmission of classical information from A to B can be associated exclusively with nonnegative relativistic intervals: since we are talking about something entirely objective, it is necessary that the direction of this transmission be determined unambiguously and not be dependent on any further arbitrary choice of anything, including the choice of reference frame.

The nonseparability of the relativistic description of spacetime gives rise to an analogy with quantum entanglement: in special relativity, the relative velocities of two arbitrary bodies are, in a certain sense, 'entangled:' if the velocity of body B relative to A is equal to v_{BA}, then the velocity v_{AB} of body A relative to B is always equal to $v_{AB} = -v_{BA}$. And when body A changes its relative velocity v_{AB} relative to body B, then the velocity v_{BA} also changes instantly, regardless of the distance between the two bodies. There is nothing surprising here, and yet it resembles nonlocality.

Obviously, a certain relation between distant events in special relativity is established due to relative velocity, although this does not indicate the presence of any physical interaction between the bodies. At the same time, the relative speed indirectly, through the redefinition of the 'present,' influences the joint probabilities, since the 'compatibility' of these probabilities itself acquires meaning only within the framework of a single relativistic 'present,' which is determined only conditionally after the choice of one or another RF.

Thus, in the relativistic case, we can also speak of the uncertainty of joint probabilities, if we keep this dependence in mind. Such uncertainty persists up to the moment of measurement of the relative velocity, since up to this moment it can be instantly and arbitrarily changed by local acceleration of one of the two bodies (nuclei in the experiment considered). Only at the time moment of direct measurement does it become definitively clear in which frame of reference the relative velocity will be measured, since the possibility of changing the local velocity of one of the bodies also means the possibility of changing its proper frame of reference up to the moment of measurement. This situation is reminiscent of the measurement collapse of a quantum state: there, too, the settings of a nonseparable system can be changed by local actions up to the moment of measurement, which, in turn, requires that the propagation of the measurement collapse in space not be limited by the speed of light c. Otherwise, the propagation of the collapse might not have kept pace with new local changes in the quantum system's settings, and the joint probabilities could not have been determined unambiguously by measurement.

The physical mechanism for the violation of the quantum-physical law of quantum mechanics in special relativity can be represented geometrically: on each of the two distant worldlines of the nuclei, a point-event is defined, corresponding to the instant of decay. Let the world lines before decay be labeled $-$, and after decay, $+$. The 'present' is a three-dimensional hyperplane in four-dimensional spacetime intersecting these two world lines. Depending on the coordinate velocity of the body, we must consider one or the other hyperplane to be its 'present.' Consequently, the 'present' can intersect two world lines in different ways in the sections of world lines we labeled $(-+)$, $(--)$, $(+-)$, $(++)$. When moving to calculations in the proper reference frames of two atoms, the coordinate velocities will become equal to the relative ones. The relative velocity will determine how much time during the experiment the hyperplane of the common 'present' will belong to one or another of the four variants: if longer, the probability of this case, calculated for a set of homogeneous experiments with nuclei, will be greater; if shorter, it will be smaller. Since the probability distributions necessary for calculating correlations are constructed pairwise, correlations for three or more atoms will necessarily be calculated based on different distributions corresponding to different pairs of atoms and different 'presents,' which leads to uncertainty of properties before the moment of measurement and to a violation of the local realism inequalities. The point is that, as shown in Ref. [23], it is not always possible to combine three or more distributions into one without changing the pairwise relative probabilities. If the pairwise joint probabilities obtained during measurement are reduced to one arbitrarily chosen reference frame, then, naturally, the effect of the violation of inequalities will disappear, but the resulting distribution and the correlations calculated based on it can no longer be considered the result of a direct measurement. A change in the relative velocity by local acceleration of one of the nuclei in the system is sufficient for the correlation to instantly change: a pair correlated by the fact of joint distribution may become anticorrelated, or vice versa. Moreover, two atoms may be separated by an arbitrarily large distance, so that an arbitrarily long time may be required to transmit classical information about the change in the velocity of one of the atoms. Nevertheless, from the moment when one of the atoms in the pair has changed its velocity, which has led to a change in the relative velocity of the two atoms, we must change our calculations, take this new fact into account, and recalculate the joint probabilities in any of the proper RFs of the pair of atoms. This again resembles the logic of measurement collapse in quantum mechanics, when not only the correlations of events in the entire volume of the hyperplane of the 'present' are recalculated, but also for events that have already occurred in the past, as shown, e.g., in the analysis of teleportation experiments [24].

Importantly, this type of nonlocality differs from Albert Einstein's mysterious 'Spooky Action at a Distance,' since there is no direct action in this case. Here, it would be more appropriate to say that bodies correctly 'sense' their velocity relative to other bodies, since this is how we describe the system based on spacetime symmetry. This is a weaker assumption than true 'action at a distance,' and therefore it would be more appropriate to call this type of nonlocality 'weak nonlocality.' The associated violations of local realism inequalities in special relativity, as in quantum mechanics, clearly follow from the formalism of the theory, indicating certain parallels between the two theories.

This 'sense at a distance' can be called a kind of 'common knowledge' between bodies and the space of velocity magnitudes and directions, which must be attributed to bodies based on our notions of symmetry, and therefore it is difficult to call it 'action.' Although, when comparing with the quantum case, wave function reduction also can hardly be called immediate 'instantaneous action at a distance' [10].

4. Conclusions

Statistical correlation between measurement results at two distant points, A and B, occurs at the time of measurement and propagates with infinite velocity in the proper reference frame of the measuring instrument. In all other canonical RFs, the velocity v of correlation propagation will not be infinite, but according to special relativity, will possibly be $v > c$, thus maintaining the invariance of spacelike intervals between measurements at A and B, when these intervals are really chosen spacelike.

Such nonlocality follows from the nonseparability of quantum systems and systems described by special relativity, and, unlike Einstein's formulation of "Spooky Action at a Distance," it does not contradict special relativity. At the same time, a unidirectional superluminal transmission of information from a particle at A to a particle at B would contradict the description objectivity, since in different reference frames opposite directions of transmission would be obtained.

If in the future any considerations are found that force us to sacrifice nonlocality in favor of some other explanation for the superluminal correlations that arise in relativistic systems, then by the same logic we must also act with respect to correlations in quantum mechanics, since the physical conclusions about the nonseparability of systems leading to nonlocality in STR are analogous to those in QM. In a general physical sense, we are talking about the representation of Hilbert space and space-time as categories inextricably related both to each other and to the properties of matter itself [25].

After this text was sent to the editor, an interesting article appeared in Nature [27], describing a wide range of interpretations of quantum mechanics that currently exist.

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