Relativistic nonlocality (RNL) in experiments with moving polarizers and 2 non-before impacts

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Abstract

RNL is a recently proposed relativistic nonlocal description, which unifies relativity of simultaneity and superluminal nonlocality (without superluminal signaling). In this article RNL is applied to experiments with so-called 2 non-before impacts, leading to new rules of calculating the joint probabilities, and predictions conflicting with quantum mechanics. A real experiment using fast moving polarizing beam-splitters is proposed.

Keywords: relativistic nonlocality, timing-dependent joint probabilities, experiments with moving polarizers, 2 non-before impacts.

1 Introduction

According to quantum mechanics (QM) there are two fundamental rules of calculating the distribution of the outcomes in an experiment:

1. If one cannot distinguish (even in principle) between different paths from source to detector, the amplitudes for these alternative paths add coherently (sum-of-probability-amplitudes rule, also called superposition principle), and in multiparticle experiments nonlocal correlations appear. If it is possible in principle to distinguish, the probability of a determined outcome is the sum of the probabilities for each alternative path (sum-of-probabilities rule), and in multiparticle experiments nonlocal correlations appear.

2. The quantum formalism entails insensitivity to the state of movement of the preparing and measuring devices.

In a previous article it was argued that this view of the relationship between entanglement and indistinguishability is not the only possible one, and the principles of an alternative nonlocal description were presented. According to it entanglement depends not only on indistinguishability but also on the timing of the impacts at the beam-splitters, and especially on the velocities of these. Key notions are those of before and non-before impacts at the beam-splitters. An experiments with 2 before impacts involving one fast moving polarizing beam-splitter was proposed.

In this article it is shown how the alternative description works in a 2 non-before experiment: To account for the specific timing it uses neither the sum-of-probabilities rule, nor the sum-of-probability-amplitudes rule, but a new one. Thus the proposed alternative description offers more possibilities to calculate the distribution of the outcomes than does quantum mechanics, and yields predictions conflicting with it.

Since relativity of simultaneity and (superluminal) nonlocality (without superluminal signaling) are the basic features of the proposed alternative description, it is called Relativistic Nonlocality (RNL).
2 Basic notions and principles of RNL

We consider an experiment with entangled particle pairs in which each beam-splitter can move fast, and change from one inertial frame to another. The beam-splitters are labeled $BS_i$, $i \in \{1, 2\}$, and the corresponding detectors $D_i(+1)$ and $D_i(-1)$. The proposed RNL is based on the following definitions, principles and rules:

2.1 Before and non-before impacts

If it is in principle impossible to know to which prepared sub-ensemble a particle pair belongs by detecting each particle after leaving the corresponding $BS_i$, then the impacts at the splitters are referred to as originating indistinguishability or uncertainty, and labeled $u_i$. If it is in principle possible to know to which prepared sub-ensemble a particle pair belongs by detecting each particle after leaving the corresponding $BS_i$, then the impacts at the beam-splitters are referred to as making possible distinguishability, and labeled $d_i$. At the time $T_i$ at which a particle $i$ arrives at $BS_i$, we consider whether in the inertial frame of this beam-splitter particle $i$ has already made an impact at $BS_j$ or not, i.e., whether $(T_i \geq T_j)_i$, or $(T_i < T_j)_i$, the subscript $i$ after the parenthesis meaning that all times referred to are measured in the rest frame of $BS_i$. We introduce the following definitions:

Definition 1: the impact of particle $i$ in $BS_i$ is a before event $b_j$ if either $(T_i < T_j)_i$, or the impacts of the particles are $d_1$ and $d_2$ ones.

Definition 2: the impact of particle $i$ in $BS_i$ is a non-before event $a_j$ if:

1. $(T_i \geq T_j)_i$, and
2. the particles produce $u_1$ and $u_2$ impacts

2.2 Measurable joint probabilities of coincidence counts and unmeasurable conditional probabilities

An experiment $e$ will be labeled by indicating the kind of impact each particle undergoes, e.g., $e = (a_1, b_2)$.

A detection of a pair producing either outcome $(+1,+1)$ or $(-1,-1)$ is said to yield total value $+1$ (or value $+$); a detection of a pair producing either outcome $(+1,-1)$ or $(-1,+1)$ is said to yield total value $-1$ (or value $-$).

A detection of a pair producing either outcome $(+1,+1)$ or $(-1,-1)$ is said to yield total value $+1$ (or value $+$); a detection of a pair producing either outcome $(+1,-1)$ or $(-1,+1)$ is said to yield total value $-1$ (or value $-$).

Expressions like $P_{e_{\sigma\omega}}$, $\sigma, \omega \in \{+, -\}$, denote the probabilities to obtain the indicated coincidence detection values in experiment $e$ (i.e., particle 1 is detected in $D_1(\sigma)$, particle 2 in $D_2(\omega)$). $P_{e_{\sigma}}$ denote the probability to obtain the total detection value $\sigma$ in experiment $e$. In a similar way, we write $P^{QM}_{e_{\sigma\omega}}$ for the probabilities predicted by standard QM for experiment $e$ (note that in this case the impacts will be referred to only by $u_i$ or $d_i$, since QM doesn’t consider differences in timing). The $P_{e_{\sigma\omega}}$ quantities can be evaluated directly by measuring the corresponding count rates in the corresponding experiment.

Further we denote by $P_{e_{\sigma\omega}}(a_i, b_j)$ the probability that a particle pair that would have produced the outcome $(\sigma, \omega)$ in a $(b_i, b_j)$ experiment, produces the outcome $(\sigma', \omega)$ if the experiment is a $(a_i, b_j)$ one. Evidently, these conditional probabilities cannot be evaluated from count rates, because if experiment $(b_i, b_j)$ is performed on a determined particle pair, then it is no longer possible to perform experiment $(a_i, b_j)$ on the same pair. However, as we will see in section 3, RNL allow us to establish rules calculating conditional probabilities from measurable quantities.

2.3 The nonlocal links behind the correlations

Bell experiments with time-like separated impacts at the splitters have already been done [1], demonstrating the same correlations as for space-like separated ones. Consider an experiment in which the choice particle 2 makes in $BS_2$ lies time-like separated after the choice particle 1 makes in $BS_1$. It is clear that at the time particle 1 makes its choice, it cannot account for choices in $BS_2$ because such choices do not exist at all, from any observer’s point of view. In this case expressions like ‘the later choice’, and ‘the former choice’ make the same sense in every inertial frame. Therefore, it is reasonable to assume that the correlations appear because particle 1 has to choose as it would choose in the absence of non-local influences, and the choice particle 2 makes, depends somewhat on the choice particle 1 has made.

Inspired by this explanation we introduce now the following principles to account for the correlations when the impacts lay space-like separated:
Principle I: if the impact of a particle $i$ at $BS_1$ is a $b_1$ impact, then particle $i$ produces values taking into account only local information, i.e., it does not become influenced by the parameters particle $j$ meets at the other arm of the setup.

Accordingly:

$$P(b_1, b_2)_{\sigma \omega} = P^{QM}(d_1, d_2)_{\sigma \omega}.$$ \hspace{1cm} (1)

Principle II: if the impact of a particle $i$ at $BS_2$ is a $a_i$ impact, then particle $i$ takes account of the time at which particle $j$ actually produces, and the values particle $j$ produces in a $b_j$ impact are correlated according to the standard quantum mechanical entanglement rules.

Therefore, the following correlation rule must hold:

$$P(a_1, b_2)_{\sigma \omega} = P(b_1, a_2)_{\sigma \omega} = P^{QM}(u_1, u_2)_{\sigma \omega}. \hspace{1cm} (2)$$

Notice that in all interference experiments performed till now both splitters were at rest, and one of the impacts did happen always before the other. Eq. 2 guarantees that RNL yields the same predictions than QM for all experiments already done.

Principle III: The choice particle $i$ makes does not take into account the choice particle $i$ itself would have made if the impact would have been a before one, i.e:

$$P\left((a_i)_{\sigma'}|(b_i, b_j)_{\sigma \omega}\right)$$
$$= P\left((a_i)_{\sigma'}|(b_i, b_j)(-\sigma)\omega\right)$$
$$= P\left((a_i)_{\sigma'}|(b_j)_{\sigma'}\right). \hspace{1cm} (3)$$

As argued in [3], by assuming Principle I and Principle II we implicitly discard firstly the hypothesis that the values produced by a particle, say particle 1, do depend on the state of movement of the detectors $D_1$ monitoring $BS_1$, and secondly the hypothesis that the values produced by particle 1 depend on the time at which particle 2 impacts at a detector $D_2$, monitoring $BS_2$.

Suppose now that both impacts are non-before events. It would be absurd to assume together that particle 1 chooses taking account of the choice particle 2 has really made. Therefore we assume that particle 1 makes its choice in $BS_1$ taking into account the choice particle 2 would have made in $BS_2$ if the impact at this beam-splitter would have been a before event, but that this choice of particle 1 is independent of the choice particle 2 makes in the actual non-before impact. Similarly particle 2 makes its choice in $BS_2$ depending on which choice particle 1 would have made in $BS_1$ if the impact at this beam-splitter would have generated a before event, but independently of the choice particle 1 makes in the actual non-before impact.

These assumptions can be expressed through the following key equation:

Principle IV:

$$P(a_1, a_2)_{\sigma' \omega'} = \sum_{\sigma, \omega} P(b_1, b_2)_{\sigma \omega}$$
$$\times P\left((a_1)_{\sigma'}|(b_2)_{\omega}\right)P\left((a_2)_{\omega'}|(b_1)_{\sigma}\right). \hspace{1cm} (4)$$

According to Eq. (1), in a 2 before experiment the joint probabilities of coincidence detections are calculated through sum-of-probabilities. According to Eq. 2 in a 1 before 1 non-before experiment the joint probabilities of coincidence detections are calculated through sum-of-probabilities-amplitudes. In Section 3 it is shown that in certain experiments with 2 non-before impacts Eq. 4 yields a new rule that involves together sum-of-probabilities and sum-of-probability-amplitudes.

It is worthy to highlight that RNL always involves instantaneous influences even when the outcomes distribution is calculated through sum-of-probabilities.

### 2.4 Impossibility of communication without observable connection (signaling)

RNL assumes further

Principle V:

$$P(a_i)_{\sigma} = P(b_i)_{\sigma}. \hspace{1cm} (5)$$

The physical meaning of Eq. (5) is the following: a human agent at place A cannot produce observable order (a message) at place B, if there is no observable connection (signaling) between A and
B. Accordingly, communication between (time-like or space-like) separated human observers requires energy propagating in space-time from one observer to the other. Indirectly this principle leads also to the impossibility of using nonlocality for superluminal signaling. Notice, however, that the principle works also in situations with time-like separated measurements as for instance when the impact at $BS_2$ lies time-like separated after the detection at one of $D_1$. In such experiments interference fringes at the level of the single detection (first-order correlations) would not imply any superluminal signaling. However, since there is no observable connection or signaling between any $D_1$ and $BS_2$, first order interference fringes would imply subluminal signal-less communication (i.e. the possibility of using energyless or unobservable connections for generating observable order). The motivation of Eq. (5), therefore, is primarily not the concern of limiting the speed of signaling, but rather to forbid communication without signaling.

The impossibility of superluminal signaling is in physics a consequence of the dependence of simultaneity on the inertial frame (or the impossibility of absolute time) resulting from observations like those of Michelson-Morley. This relativity of simultaneity (and therefore the impossibility in principle of superluminal signaling) enters evidently into RNL through the definition of before and non-before impacts.

QM is a "specifically nonrelativistic" theory [2], and the concern of forbidding faster-than-light communication between human observers was foreign to its construction. That quantum formalism conspires to combine nonlocality with the impossibility of superluminal signaling [3] has the appearance of a "deep mystery" [2] making possible a "pacific coexistence" [3] between quantum mechanics and relativity. The spirit of RNL is somewhat the reverse: (superluminal) nonlocality, the impossibility of communication without signaling, and constant $c$ as the upper limit for signaling are considered from the beginning to be fundamental principles of the physical reality, and the formalism has to adapt to them. They determine in particular the path amplitudes and the possible correlations rules [3].

\begin{theorem}
\begin{equation}
P((a_i)_{\sigma}|(b_j)_{\omega}) = \frac{P(a_i, b_j)_{\sigma\omega}}{P(b_j)_{\omega}} \tag{6}
\end{equation}
\end{theorem}

\textbf{Proof:} Conditional probabilities are related to measurable quantities through the equation:

\[ P(a_i, b_j)_{\sigma\omega} = P(b_i, b_j)_{\sigma\omega}P((a_i)_{\sigma}|(b_i, b_j)_{\sigma\omega}) + P(b_i, b_j)_{(-\sigma)\omega}P((a_i)_{\sigma}|(b_i, b_j)_{(-\sigma)\omega}) \]

Taking into account (3) one is led to

\[ P(a_i, b_j)_{\sigma\omega} = \left[P(b_i, b_j)_{\sigma\omega} + P(b_i, b_j)_{(-\sigma)\omega}\right] \times P((a_i)_{\sigma}|(b_j)_{\omega}) = P(b_j)_{\omega}P((a_i)_{\sigma}|(b_j)_{\omega}) \]

q.e.d.

For "maximally entangled states" in which the particles are prepared equally distributed in two classes of pairs, it holds that:

\[ P(b_i)_{\sigma} = P(b_i)_{-\sigma} = \frac{1}{2}P(a_i, b_j)_{\sigma\omega} = P(a_i, b_j)_{(-\sigma)(-\omega)} \tag{7} \]

Then from Eq. (3) follows:

\begin{corollary}
\begin{equation}
2P(a_i, b_j)_{\sigma\omega} = 2P(a_i, b_j)_{(-\sigma)(-\omega)} = P((a_i)_{\sigma}|(b_j)_{\omega}) = P((a_i)_{-\sigma}|(b_j)_{-\omega}) \tag{8}
\end{equation}
\end{corollary}

\begin{theorem}
For experiments with particles prepared equally distributed in two classes of pairs it holds that:

\[ E(a_1, a_2) = E(b_1, b_2)E(a_1, b_2)E(b_1, a_2), \tag{9} \]

where each $E(e)$ denotes the correlation coefficient $E = \sum_{\sigma, \omega = \pm 1} \sigma\omega P(e)_{\sigma\omega}$.

\textbf{Proof:} Expanding in $E(a_1, a_2)$ each of the four $P(a_1, a_2)_{\sigma\omega}$ terms according to (8) yields:

\[ E(a_1, a_2) = \sum_{\sigma, \omega = \pm 1} \sigma\omega P(b_1, b_2)_{\sigma\omega} \times \left[ P((a_1)_{\sigma}|(b_2)_{\omega}) - P((a_1)_{-\sigma}|(b_2)_{\omega}) \right] \times \left[ P((a_2)_{\omega}|(b_1)_{\sigma}) - P((a_2)_{-\omega}|(b_1)_{\sigma}) \right] \]

3 Theorems

We derive now theorems that allow to calculate conditional probabilities and the correlation coefficients in experiments with 2 non-before impacts.
Applying Eq. (8) leads to:

\[
E(a_1, a_2) = \left( \sum_{\sigma, \omega = \pm 1} \sigma \omega P(b_1, b_2)_{\sigma \omega} \right) \\
\times \left[ P\left( (a_1)_\sigma ^{|(b_2)\sigma}\right) - P\left( (a_1)_{-\sigma} ^{|(b_2)\sigma}\right) \right] \\
\times \left[ P\left( (a_2)_{\omega} ^{|(b_1)\omega}\right) - P\left( (a_2)_{-\omega} ^{|(b_1)\omega}\right) \right] \\
= \left( \sum_{\sigma, \omega = \pm 1} \sigma \omega P(b_1, b_2)_{\sigma \omega} \right) \\
\times \left( \sum_{\sigma, \omega = \pm 1} \sigma \omega P(a_1, b_2)_{\sigma \omega} \right) \\
\times \left( \sum_{\sigma, \omega = \pm 1} \sigma \omega P(b_1, a_2)_{\sigma \omega} \right) \\n\]
q.e.d.

Notice that Eq. (8) is the product of the expression \(E(b_1, b_2)\) that works as the quantum mechanical sum-of-probabilities, and the expressions \(E(a_1, b_2)\) and \(E(b_1, a_2)\) that work as quantum mechanical sum-of-probability-amplitudes.

4 Predictions: Conflict (and agreement) between RNL and QM

Consider now a 2 non-before experiment with entangled polarized photons in which two classes of photon pairs, \((H_1, H_2)\) and \((V_1, V_2)\), are prepared through down-conversion in the "Bell state":

\[
|\phi\rangle = \frac{1}{\sqrt{2}}(|H_1, H_2\rangle - |V_1, V_2\rangle) \\
\]
(10)
where \(H\) and \(V\) indicate horizontal and vertical polarization, respectively. The polarizing beamsplitters (BS\(_1\) and BS\(_2\)) are vertical oriented, and preceded by half wave plates, which rotate the polarization of the photons by angles \(\alpha, \beta\).

As said, the quantum formalism does not depend at all on the timing of the impacts of the particles at the beamsplitters. The correlation coefficient is assumed to be given by the Lorentz-invariant expression \(\phi\) and \(\psi\):

\[
E^{\text{QM}} = \sum_{\sigma, \omega} \sigma \omega P^{\text{QM}}(u_1, u_2)_{\sigma \omega} = \cos 2(\alpha + \beta). \\
\]
(11)

Consequently, for \(\alpha + \beta = 0\), QM predicts perfectly correlated results (either both particles are transmitted, or they are both reflected) for an experiment with 2 non-before impacts.

Substituting (8) and (9) in equation (8) leads to the correlation coefficient:

\[
E = \cos 2\alpha \cos 2\beta \cos^2 2(\alpha + \beta). \\
\]
(12)

Consequently, according to RNL, \(\alpha + \beta = 0\) will not produce \(E = 1\), i.e. perfectly correlated results. In particular, for \(\alpha = -\beta = 45^\circ\) one gets \(E = 0\), i.e. the four possible outcomes \((+1, +1), (+1, -1), (-1, +1), (-1, -1)\) equally distributed.

In summary, for \(\alpha = -\beta = 45^\circ\) QM and RNL lead to the clearly conflicting predictions as well for the 2 before experiment described in [3], as for the 2 non-before one.

Notice however that for \(\alpha = \beta = 22.5^\circ\), RNL and QM lead to the same predictions in case of a 2 non-before experiment, but to conflicting predictions in case of a 2 before one.

5 En route towards a real relativistic nonlocality experiment

A real experiment with 2 non-before impacts could be done with the same setup of the 2 before experiment. The arrangement is represented in Fig. 1. It is assumed that the particles are channeled from the source to the beamsplitters by means of optical fibers, and that the optical path S-BS\(_1\) traveled by particle 1, is a bit longer than optical path S-BS\(_2\) traveled by particle 2.

The delay in time resulting from this path difference is labeled \(\delta t\). Beam-splitter BS\(_1\) is at rest in the laboratory frame, and therefore the impact at this splitter is a non-before one. Beam-splitter BS\(_2\) is set on a wheel so that at the moment of
the photon impact it moves with velocity \( V \) towards \( BS_1 \) (i.e. the opposite direction as in the 2 before experiment). The distance between the beam-splitters is labeled \( L \).

The condition, to ensure a non-before impact at \( BS_2 \) follows straightforward from the analysis done in [3], and is given by the equation:

\[
\delta t < \frac{VL}{c^2}. \quad (13)
\]

Latest results confirm that values of \( L \) greater than 100 km may become possible in a couple of years [4]. This would mean for velocities of about 100 m/sec (360 km/h) that \( \delta t \) could reach values of 111 ps. Such an accuracy in measurement does not seem to be an insurmountable challenge, especially if the increasing interest on quantum optics reaches the levels which particle physics enjoys at present, and yields comparable budgets.

In conclusion: While RNL formulates its principles taking account explicitly of the relativity of simultaneity, QM does not worry about it. Thus while QM bears only two rules to calculate the joint probabilities of coincidence detections, RNL can generate additional ones and account for different timings. And so whereas both pictures agree for all the experiments already done, they lead to conflicting predictions regarding relativistic nonlocality experiments. All this seems to suggest that the basic character of QM may be that of an application of RNL to particular situations. Anyway the fact that RNL unifies consistently relativity of simultaneity and superluminal nonlocality speaks in favor of continuing the effort to do the proposed relativistic experiments. In particular it seems worthwhile to study whether satellites could allow us to perform the experiment with much higher velocities [1]. More deeper analysis to clarify whether the experiment is possible even with values of \( L \) similar to those used in [10] is in progress too [12]. The suggested possibility of 2 non-before experiments through particles impacting successively at 2 beam-splitters at rest [3], is further discussed in another article.

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[12] Discussions are taking place with Nicolas Gisin, Wolfgang Tittel and Hugo Zbinden.