On a modification of the quantum eraser experiment, the results of which may disprove the absoluteness of measurement in quantum mechanics.

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Abstract

This article considers a hypothesis of nonlocality, which should be described by Lorentz-invariant equations with infinite-order derivatives. It is shown that, despite formal Lorentz invariance, such a description, while preserving causality, must lead to local violation of the relativity principle. Such violations would be limited by the radius of nonlocality of each source of nonlocal phenomena. There would be no single common preferred reference frame, and on average the relativity principle would hold. This hypothesis allows for an interpretation of the results of the delayed-choice version of the quantum eraser experiment. To test this hypothesis, a modified scheme for the quantum eraser experiment is proposed. If the hypothesis is correct, the experimental results will differ from the predictions of quantum mechanics.

Keywords:non-locality, Quantum Eraser Experiment.

1 Introduction

The double-slit quantum eraser experiment is a variation of the Young's experiment, demonstrating how observing a particle's path information destroys the interference pattern, and its "erasure" restores it. The experiment demonstrates wave-particle duality and quantum entanglement. There also exists a "delayed-choice" variant, where the choice to erase the information or not is made after the photon has already passed through the slits, with the interference pattern appearing or disappearing accordingly. This experiment is a variation of the classic double-slit experiment that shows that the decision for a particle to behave as a wave or as a particle can be delayed and even reversed after it has already passed through the slits. The results of such experiments are considered within the framework of the concept of Bell's inequalities violation and the absence of hidden parameters [1-4]. It is assumed that if the behavior of photons were determined by hidden parameters (i.e., they "agreed" at the start), then the statistics would satisfy Bell's inequalities.

However, in deriving this conclusion, one implicit assumption is made, discarding as "meaningless" the supposition that when an entangled photon pair is created, they could have access to information about the presence and orientation of polarizers in their path at a distance, without having reached them yet. Then, having this information, the photons could form their polarization directions not randomly in space, but in a correlated manner, matching the predictions of quantum mechanics. That is, the assumption is that the measurement of polarizations occurs already at the moment the entangled pair is created. However, introducing a polarizer into the path of one of the photons later would not affect the polarization of the second photon. This would distinguish the consequence of such a hypothesis from quantum mechanics, where the main process is the measurement at the moment the photon passes through the polarizer. Such "meaningless" assumptions are immediately discarded as violating Special Relativity (SR), although experiments on nonlocality might precisely be the domain where SR violations occur. And this assumption is not tested experimentally. The article proposes an experimental scheme that could refute or confirm this assumption. It also considers how SR could be violated in this case.

2 On a Possible Modification of the Quantum Eraser Experiment Scheme to Test the Hypothesis

To test the hypothesis, the following modification of the known quantum eraser experiment scheme [4] is proposed.

In this experiment, entangled photons are generated by a process called spontaneous parametric down-conversion. This occurs in a special crystal, beta-barium borate (BBO). Two entangled photons (702.2 nm) are produced. These two photons fly apart in two different directions. In this experiment, one direction is denoted as p, and the other as s. Photons moving along the p path are called p-photons here, and those moving along the s path are called s-photons. The double-slit interference pattern is created by the s-photons. They pass through the double slit to the detector D_s. The p-photons go directly to the detector D_p. If polarizers that disrupt interference (QWP1, QWP2) are placed in front of each of the two slits in the path of the s-photon, then interference is not observed in the absence of a polarizer in the path of the p-photon. Introducing a polarizer into the path of the p-photon restores the interference pattern of the s-photon. The experimental scheme with the polarizer introduced into the p-photon path is shown in Fig.2. The commonly accepted reason for this phenomenon is considered to be the act of measuring the polarization of the p-photon. In doing so, as mentioned above, the assumption is discarded as "meaningless" that when the entangled photon pair is created, they could have access to information about the presence and orientation of polarizers in their path at a distance, without having reached them yet. Then, having this information, the photons could correlatively form their polarization directions in a manner consistent with quantum mechanics. To test this assumption, it is proposed to introduce the polarizer that restores the double-slit interference after a significant time interval has passed since the entangled photon pair was emitted from the BBO source. At this point, the polarization of the entangled pair would have already been formed. To prevent any information transfer to the s-photon before the p-photon arrives at the polarizer, its path must be physically blocked. Let us denote, in the laboratory reference frame, the time of emission of the entangled photon pair (Fig.1) with the polarizer absent from the p-photon path as t_1. And the time of placing the polarizer in the path of the p-photon, before its arrival at the detector D_p, as t_2 (Fig.2), with the information path blocked. If the time interval $t_2 - t_1$ is sufficiently large, then, if the above-described "meaningless" assumption is correct, the interference pattern of the s-photon will not appear. If the absolute nature of the measurement act is correct, corresponding to quantum mechanics, the interference pattern will be preserved.

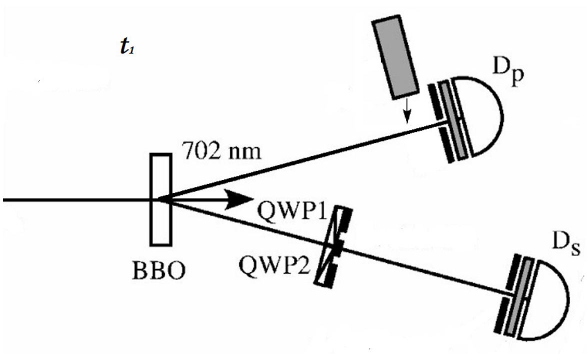

Figure 1: Fig.1. Moment of time t_1 of the emission of the entangled photons. The polarizer that restores the interference pattern of the $s-$ photons is not yet in the path of the $p-$ photon.

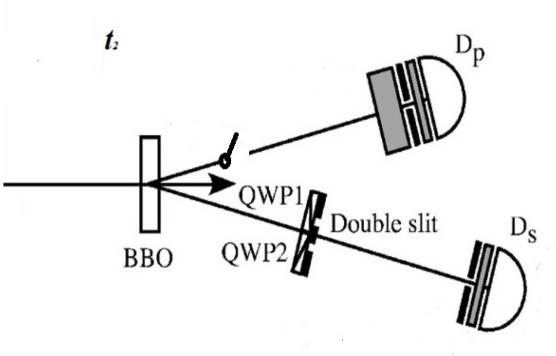

Figure 2: Fig.2. Moment of time t_2, when the polarizer is already placed in the path of the $p-$ photon, before its arrival at the detector D_p.

3 On the Consequences of Introducing Infinite-Order Derivatives

The assumption that photons can "feel" the presence and orientation of polarizers at a distance is only possible within a certain mathematical formalism describing this. If photons are described using some differential equations, the order of the derivatives in them must be infinite. Let us consider the most general properties of such a formalism, distinguishing it from equations with finite derivatives. Such equations must use only Lorentz-invariant operators to preserve Lorentz invariance on average. For example, of the form

$$(1-\frac{\Box}{\beta^2})^{\infty}u=0 \tag{1}$$

Here it will be necessary to specify the procedure for generalizing the order of derivatives to infinity and the consequences of such a procedure. For generalization, let us consider the spatially one-dimensional equation

$$u_{xx}-u_{tt}=0 \tag{2}$$

and its finite-difference approximation, coinciding with the equation as $\tau \to 0, h \to 0$

$$\frac{u_j^{i+1}-2u_j^i+u_j^{i-1}}{\tau^2}=\frac{u_{j-1}^i-2u_j^i+u_{j+1}^i}{h^2} \tag{3}$$

$$u_j^{i+1}=2u_j^i-u_j^{i-1}+\frac{(u_{j-1}^i-2u_j^i+u_{j+1}^i)\tau^2}{h^2} \tag{4}$$

The solution of equation (2) involves finding a new time layer u_j^{i+1} for all spatial points j, knowing the previous time layers u_j^i and u_j^{i-1}, and letting $\tau \to 0, h \to 0$. For a $2N$-th order derivative, we will find the solution on the time layer u_j^{i+N} for all j, assuming all previous time layers are known. That is, this method involves finding a new time layer using the highest-order derivative in the equation. At the same time, the new time layer depends on the old ones, which preserves causality. Letting the derivative order N tend to infinity, we obtain that the new time layer will depend on an infinite number of old time layers and an infinite number of points along the spatial axis on the current time layer. Indeed, with Lorentz invariance of differential operators, the order of spatial derivatives corresponds to the order of temporal ones. Further, letting $\tau \to 0, h \to 0$, we obtain at least a finite, or possibly infinite, radius of nonlocality, depending on the form of the function u. In this case, to preserve the principle of causality, the principle of relativity and the equivalence of different reference frames will not hold.

With Lorentz-invariant differential operators in such equations, a transition to another coordinate system, for example, a rotation in x, t coordinates, will lead to the value of the new time layer in the new coordinate system u_j^{i+N} depending on future time layers in the old coordinate system u_j^{i+N+k}, $k > 1$ Fig.3. Because along the new spatial axis after rotating the coordinate system, the value u_j^{i+1} will depend on an infinite number of points, and as $\tau \to 0, h \to 0$, these future time layers will be separated from layer u_j^{i+N} by a finite amount, violating the principle of causality. That is, to solve the Cauchy problem in the new coordinate system with infinite derivatives, values from the "future" will be needed. With finite derivatives, such dependence on the "future" does not exist. One could rotate and shift the coordinate system at each point of the old time layer, and the necessary data would be in an infinitesimal region (in the limit).

As a result, one reference frame will be distinguished, in which the field at one point depends on the field at other points in space, but only on their values in the present and past.

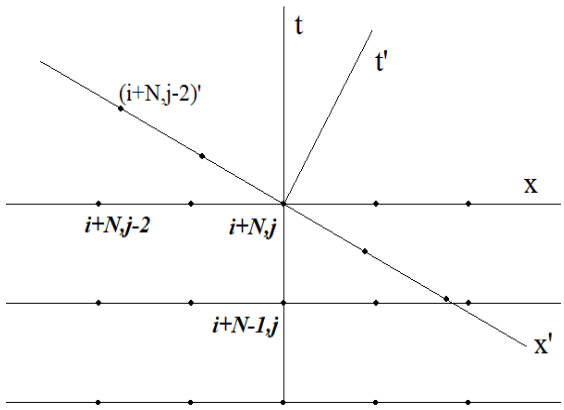

Figure 3: Fig.3. Rotation of the reference frame from x, t to x', t'.

Thus, with such a generalization of infinite derivatives as described above, we obtain a situation where, with Lorentz-invariant operators and while preserving the principle of causality, the principle of relativity will not hold. Such violations will be limited by the radius of nonlocality of each source of nonlocal phenomena. At the same time, there will be no single common preferred reference frame, assuming that the system in which nonlocality manifests is not unique, and on average the principle of relativity will hold due to the Lorentz invariance of the differential operators. That is, violations of the relativity principle may be barely noticeable, as they may only manifest when quantum nonlocality is fixed. In this case, the motion of the polarizer on the path of p-photons relative to the stationary photon source (Fig.1) and the motion of the photon source with a stationary polarizer will not be equivalent, even with the constancy of the speed of light in all reference frames.

Thus, to restore causality and depart from the generally accepted model, in which interference results can be canceled and restored even after the detection of s-photons, one has to assume local violations of the principle of relativity. Violations of Lorentz invariance [5-6] are usually sought and assumed at high energies and are not typically assumed in experiments demonstrating nonlocality. Although experiments with nonlocality might be precisely such a domain, with violations of SR, even with the constancy of the speed of light in all reference frames.

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