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ON NONLOCALITY OF QUANTUM OBJECTS

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Abstract

We present an option of the experiment with a correlated pair of particles in the entangled state, which provides the effect of a change in the polarization for entangled photons, and demonstrate the reality of all different superposition states and the corresponding vector of the quantum system state; also we analyze possible consequences of this fact. We propose a quantum realism paradigm within the relational paradigm instead of the local realism concept disproved by the experiments on verifying the Bell inequalities. We analyze the results of experimental research of the Leggett inequality violation with respect to the verification of the adequacy of different kinds of nonlocal hidden variable theories and suggest a new way of their evaluation based on the study of the photon cross-correlation suppression after a beam splitter and preparation of quantum squeezed states. We show that the interpretation based on the nonlocal hidden variable theory is inconsistent.

Keywords: quantum particles, quantum entanglement, quantum squeezed states, nonlocality, Copenhagen interpretation, relational paradigm, hidden variables, quantum state vector, physical reality.

1. Introduction

Quantum measurements possess a certain typical property distinguishing them from ordinary classical measurements — until the moment of measurement (a priori), a physical variable does not have any particular value unless it is in an eigenstate of the measured variable (see, e.g., [1–3] and the references therein). This property (not the statistical character of measurements) outlines the quantum theory as a separate chapter of contemporary physics. Otherwise, it would just be a subsection of statistical physics. This property is exactly in full accordance with the Copenhagen interpretation of quantum theory.

In accordance with the von Neumann projection postulate [4], the quantum-state-vector collapse happens at the moment of measurement, i.e., its dimensionality reduces to the measured range of values of the variable under measurement (see, e.g., [3, 5] and the references therein). The collapse of the quantum state of a pair or more correlated particles in an entangled state usually elicits special interest because a measurement on one particle results in an instant change of the quantum state of another one (or others) separated from the first one at an arbitrary (perhaps significant) distance. The von Neumann projection postulate, strictly speaking, does not describe such a reduction. Its generalization for entangled states was suggested by Khalili [6], but the general conclusion on immediate reduction remains valid. That is why the attempts at creating faster than light (FTL) communication lines based on this phenomenon still continue (see, e.g., [7] and the references therein). We believe that a detailed

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research of this phenomenon can help to identify the features of the nonlocal nature of quantum processes. For single photons, the fact of quantum nonlocality is shown experimentally [8–10]; see also [11,12]. But new interesting effects are possible in the case of a pair of entangled particles.

The fact is that the violation of the Bell inequalities [13,14] derived under assumptions of local realism and the Kolmogorov model of probability [15,16] and captured in the experiments of Aspect et al. [17–20] as well as in the other experiments (see, for example, the last one [21]), strictly speaking, can be caused by one of the following three reasons: (a) the absence of hidden variables at possible locality, (b) the absence of hidden variables and quantum nonlocality, and (c) nonlocality in the sense of nonlocal hidden-variable theory. Logically, the experiments listed above [17–21] are not able to resolve this triple alternative per se by distinguishing one of them (for details, see [22, 23]). The dilemma seems yet extremely interesting for the other reason: It actually raises the question about the role and the degree of probability in the physical world once again. If physical experiments unambiguously show that their explanation is only possible from the perspective of the absence of hidden variables, it will clearly demonstrate that the world is really random, and thus "an electron exposed to radiation should choose, of its own free will, not only its moment to jump off, but also its direction" [24]. But, if the theory of hidden variables is still considered admissible, then ontological randomness as a property of reality will remain questionable.

Further studies revealed very strong arguments against the theory of nonlocal hidden variables [25,26], which, however, cannot completely reject it, as it is presented, because they include different modeling assumptions. But the main contenders for describing the reality and explaining the violation of the Bell inequalities are still options (a) and (b). In these cases, the particles must actually be in the superposition of all their possible states. Therefore, the analysis of the reality of existence of quantum objects before the moment of their registration and the status of the quantum-system-state vector is a question of certain interest: Is it just an element of virtual reality suitable only as a tool for corresponding calculations, or does it actually describe existing states of quantum objects?

2. What Happens between the Birth of a Quantum Particle and Its Registration?

Consider the following experiment shown in Fig. 1. We take two photons with anticorrelated polarizations in an entangled state,

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle_x^a|1\rangle_x^b|1\rangle_y^a|0\rangle_y^b + |1\rangle_x^a|0\rangle_x^b|0\rangle_y^a|1\rangle_y^b\right), \tag{1}$$

where the indices a and b refer to the first and second photon of the entangled pair, respectively, and the mutually orthogonal transverse directions x and y define the orthogonal directions of polarization. The structure of this state vector is such that the directions of the x and y polarizations of each photon of the pair a or b are equally probable, i.e., they are strictly tied (more exactly, anticorrelated) because their polarization planes are mutually orthogonal.

Such states are usually prepared by parametric scattering of light during nonlinear interaction of the second type (see, e.g., [27] and the references therein).

Now we install in one channel, say a, a phase half-wave polarization plate oriented so that the planes of polarization of its ordinary and extraordinary rays are at $\pi/4$ to the corresponding piezocrystal planes. The plate will turn the polarization plane by $\pi/2$. We do not take into account the change of polarization

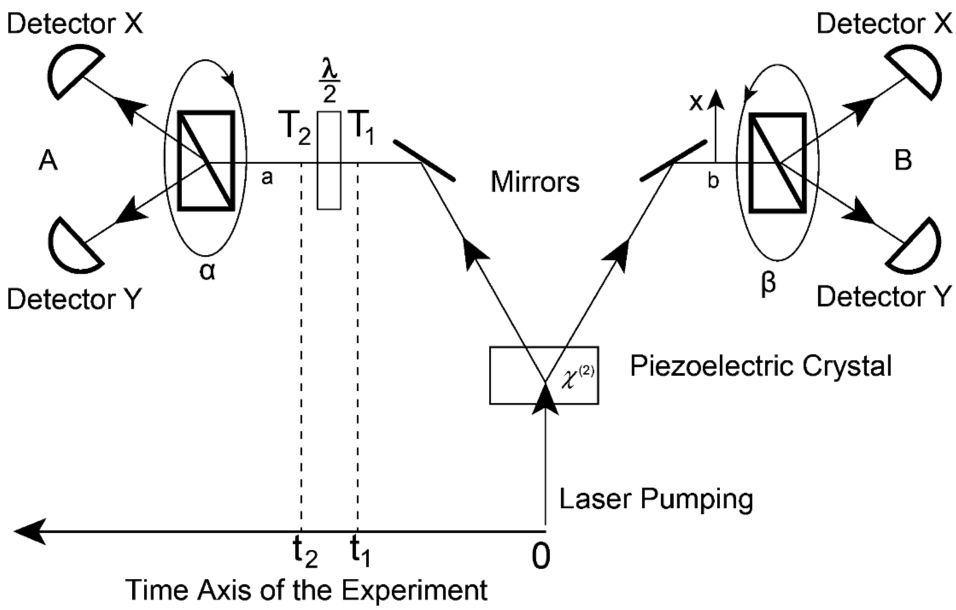

Fig. 1. A method to study correlated pairs of photons. A nonlinear crystal with the second-order nonlinearity (usually a piezoelectric crystal) under laser pumping generates pairs of photons in an entangled state. The signal photon (a) and the idler photon (b) have mutually orthogonal planes of polarizations. They are pointing at observer A and observer B, respectively. Each observer has a Wollaston prism, separating mutually orthogonal polarizations, and two detectors: x and y. The angular orientation of the observers' prisms is identical and is defined by angles of rotation $\alpha = \beta$ around the photon-propagation direction. A phase half-wave polarization plate is installed in channel A. The polarization planes of its ordinary and extraordinary rays are oriented at an angle of $\pi/4$ related to the corresponding piezocrystal planes, i.e., it rotates the photon polarization plane by $\pi/2$. The time axis of the experiment is at the bottom. It shows the moments of registration (measurement) of the photon polarization b, namely, t_1 and t_2, which is always measured before. The trajectory of photon a is also marked with the conditional points, where it will be at the moment of these measurements, T_1 and T_2. It is important to perform the measurements of b so that, in the first case, photon a is located before the $\lambda/2$ plate, and in the second case, after it.

on flat mirrors because they are not necessary in an actual experiment. So, the phase plate will alter the state vector (1) as follows:

$$|\psi\rangle = \frac{1}{\sqrt{2}} \left(|1\rangle_x^a |1\rangle_x^b |0\rangle_y^a |0\rangle_y^b + |0\rangle_x^a |0\rangle_x^b |1\rangle_y^a |1\rangle_y^b \right). \tag{2}$$

After the photon a passes this $\lambda/2$ plate, we carry out the measurement in channel b. Let, for example, the photon b after the Wollaston prism be located in the channel with the y polarization. Then, after the measurement, the vector (2) is reduced to

$$|\psi\rangle = \frac{1}{\sqrt{2}} \left(|1\rangle_y^a + |1\rangle_y^b \right), \tag{3}$$

or just to $|1\rangle_y^a$, and the photon a will be located in the channel with the y polarization after the polarization prism.

If, in contrast, the photon b as a result of the measurement is located in the channel with the x polarization, the situation will be opposite.

A real experiment will undoubtedly confirm these simple reasons.

If the measured value of the quantum observable a priori does not exist, then both photons before the measurement have no polarization at all. A $\lambda/2$ plate cannot affect such a photon in any way, and therefore, after the measurement of the polarization state of the photon b, the photon a must acquire a mutually orthogonal polarization, i.e., the outcome of the experiment will be completely opposite.

Moreover, by changing the moment of registering the photon b, we can control the behavior of the photon a. Indeed, by increasing or decreasing the distance between the nonlinear crystal and the Wollaston prism with detectors in the channel b, we can control the moment of reduction of the state vector $|\psi\rangle$. If this happens before the photon a reaches the half-wave polarization plate, both photons will be registered with identical polarization states; otherwise, according to the reasons provided, they will be opposite. But, as was shown above, this will surely not happen. What does this mean?

It either means that the measured variables do possess certain values before the measurement, which would contradict the Copenhagen interpretation but is still possible, because there is no conflict with the results of Aspect, Bell, Giustina, et al., or we should conclude that, although the measured variables do not have defined values a priori, there is strict correlation between them nonetheless, i.e., we are observing, so to speak, a nonlocal correlation of all possible states of the particle superposition.

Both alternatives are surprising and, in combination with experiments on verifying the Bell inequalities, leave no room for simple local models. In the first case, we would have to talk about the theory of nonlocal hidden variables, because that would be the only way to explain the violation of the Bell inequalities observed in experiments [17–21] and the others. And the second case would assume nonlocal correlation of physical variables not possessing any particular values in the classical sense we are used to, i.e., being in the superposition to all their possible components of the state. Therefore, we would reject option (a) – the absence of hidden variables without nonlocality, because if there are no hidden variables, what is the source of superclassical correlation of measurement results for both particles? (See also [28] for more details.) However, this opinion is not shared by all scientists. An essential part of the quantum community, developing various versions of the information interpretation of quantum mechanics (see, e.g., [29–31]), follows the Copenhagen interpretation, which has the local character. However, if we consider the nonlocality as a necessary attribute of quantum effects, it is important to understand that the types of nonlocality in these cases are different in nature. The first one is the nonlocal realism, while the second incurs quantum nonlocality in the sense that it is not a simple immediate reduction of the state vector but its reduction in a certain way, with consideration for mutual correlation of entangled particles.

Now we investigate these alternatives in detail.

3. Nonlocal Realism

Nonlocal realism is what we call a state of reality, where the results of quantum processes are predetermined by a certain set of hidden variables, and the possibility of nonlocal interactions is not excluded.

It is clear that the nonlocal link between two observers A and B (Fig. 1) can have a dual nature. It can be the correlation of measuring devices of these observers or the correlation of the measurement results themselves (see also [25, 26]). What is the physical meaning of this difference?

It is well known that the correlation function of measurements of two photons correlated in polarization according to a scheme similar to the one shown in Fig. 1, but without a phase plate and with an arbitrary orientation of prisms, has the following form (see, e.g., [23, 26] and the references therein):

$$\langle AB \rangle = \cos 2\phi, \tag{4}$$

where $\phi = \alpha - \beta$ is the angle between the polarization prisms. This is a result of a strict quantum calculation, and it has been confirmed by experiments many times. No one local classical model is able to simulate this dependence (for details, see [23, 25, 26]); this fact causes the violation of the Bell inequalities by the quantum theory. This leads to a question: Can this formula be deduced not within a quantum but within a classical (let it even be nonlocal) theory? Or, in other words, can there another (classical) way to design reality so that it could also be described by formula (4)?

The answer is obvious: This reality should match formula (4) literally, i.e., be an assumption that the measurement result depends on the angle ϕ in accordance with (4). Although it contradicts the laws of physics, we model (4) exactly in this case, and the violation of the Bell inequality will fully correspond to the picture being implemented in the experiment.

But which type of nonlocality will be present in this scheme? The first one, obviously, where the measurement result depends on the mutual nonlocal correlation of measuring devices but not on the results of measurements themselves. This type of nonlocality is analyzed by Leggett [25], derived from his criteria of adequacy of predictions of the theory of nonlocal hidden variables. Later on, it was explored by the Zeilinger group experimentally [26]. It is perfectly clear how it can be rejected without even resorting to searching for possibilities of formal violations of the Leggett inequality [25]. Such type of nonlocality is adjusted to a certain kind of polarization correlation of a pair of entangled particles directed at two observers. It would be enough to change it, and the quantum law (4) will cease to hold in the considered system of nonlocal correlation of registering devices.

But how can we change the correlation function of polarization of entangled particles? It is enough to change the polarization of one of them in relation to the other one by, for example, placing a $\lambda/4$ phase plate on its path, as in the experiment [26]. In this case, the predictions of the quantum theory will not match the nonlocal correlation adjusted to a different kind of polarization. Essentially, these are the results captured in the experiment [26]. But can it unravel all the kinds of theories of nonlocal hidden variables completely? Apparently not, because it leaves the option of a nonlocal bond — dependence of the measurement results of one observer on the results of the other observer. This is perhaps the most interesting kind of nonlocal bond, which highly resembles the collapse of an entangled-particle-pair state vector at registration of at least one of these particles. So the problem of complete refutation of nonlocal hidden variable theories remains unsolved, and the theory of nonlocal realism is still one of the possible explanations.

4. A Counterexample of the Nonlocal Realism

The experiments on verifying the Bell inequalities formalized by the Einstein–Podolsky–Rosen paradox [17–21] have reliably disproved the theory of local hidden variables, i.e., the so-called local realism (see also [2, 32]). The locality hypothesis, in this case, assumes that two observers registering a pair of correlated particles (one observer registers one particle) are in no way intercorrelated, and the readings of measuring instruments of one observer do not affect the readings of the other in any way (see, e.g., [23, 33]). It is impossible to verify these assumptions within the framework of experiments based on testing the Bell theorem. Note that the absence of hidden variables at each local place is the direct consequence of the Bohr complementary principle and the Heisenberg inequality, as well as the two-slit experiment [31].

However, nonlocality has already become an experimental fact in quantum theory (in the sense of quantum nonlocality, as we have discussed before). But abandoning the locality hypothesis and accepting the nonlocal concept of hidden variables, we can easily explain the violation of the Bell inequalities (though we should note that this will not only eliminate the Copenhagen interpretation and, for example, the many-worlds interpretation in terms of consistent histories, but will also question the status of quantum theory as an independent section of modern science in general).

So, the only appeal that remaines for the supporters of the realism and actually even when it comes to knowledge about the quantum theory in the traditional classical statistical physics, is the attractiveness of the nonlocality of the unknown, the mysterious nature of the interaction, which is unaffected either by spatial or time (within the light cone) constraints. Moreover, it seems that the argument for such a point of view is that the phenomenon of quantum nonlocality has already been proved by experiments, not only for coupled particles or more entangled particles, but even for the single photon [8–10].

In addition, the result of any experiment with quantum particles can be calculated by a computer – within its probabilistic sense, of course. Moreover, a computer operates using specific values of measurable quantities, fully defined before the moment of measurement (as in classical statistical physics). That is why it is quite difficult to disprove completely the nonlocal realism or the nonlocal theory of hidden variables, which are actually one and the same thing.

On the other hand, any physicist who has ever dealt with specific quantum calculations would never believe in nonlocal realism from the perspective of his/her own experience and the inner intuition based on them. That is why, in order to disprove it, researchers have chosen the path of developing new schemes for experiments, which will more and more increase the absurd nature of models created on the basis of the nonlocal theory of hidden variables. Indeed, how, for example, could we explain the effect of dual-beam interference, taking into account the experiments verifying delayed choice or tri-beam interference [1] within the nonlocal realism? Only by the nonlocal photon jumping between separated optical channels, even through non-transparent walls [35].

Nevertheless, we will try to find a counterexample which could reveal the inconsistency of this concept.

It is well known that, due to the Heisenberg uncertainty principle, the phase (or its cosine and sine) of Fock states with a certain number of photons is completely undetermined, i.e., it is the superposition of all its possible values (see, e.g., [1, 3] and the references therein). How does the nonlocal-hidden-variable theory interpret this indisputable fact? It states that a photon in state, e.g., $|1\rangle$, possesses a certain phase, but it adjusts to a particular experimental situation in a nonlocal way, as if it knows in advance the whole subsequent history of photon transformation and measurement. This can explain not only the violation of the Bell inequalities but also various interference quantum effects. Despite the highly exotic nature of these reasons, it is very difficult to disprove them formally. We will try to do this by analyzing the effects of photocount correlation suppression [36] and the preparation of squeezed states by parametric light scattering (see, e.g., [37]).

The effect of photocount correlation suppression is a surprising and not yet completely understood (in terms of interpretation) phenomenon demonstrating the specifics of quantum theory.

It can be described as follows.

If we send a single photon to one of the inputs of a 50% beam splitter, then with a probability of $1/2$ it will appear on one of the outputs, demonstrating its quantum properties. But what if each input of the beam splitter receives a single photon at the same time? It would seem that both photons should appear

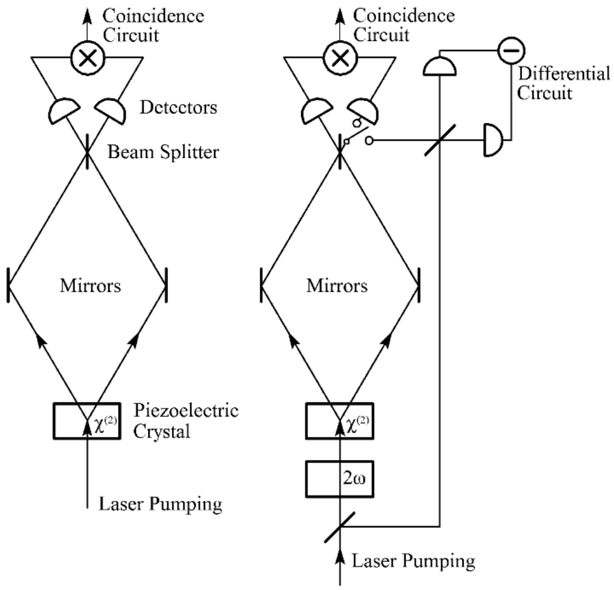

Fig. 2. Scheme for observing the effect of photon cross-correlation suppression (left) and the effect of simultaneous registration of the squeezed state (right). A nonlinear crystal (usually a piezocrystal) under laser pumping generates a pair of photons. They are directed at the beam splitter and detected. The coincidence scheme registers the simultaneous arrival of photons on both photodetectors (left). For a 50% beam splitter, the probability of such events is zero. On the right, the fluctuations of the field quadrature are recorded at the same time with a balanced homodyne detection scheme. Radiation is guided into this scheme by an operation mode switch. For matching of the mixed frequencies, frequency doubling of laser radiation should be introduced in front of the nonlinear crystal.

on the same output with probability 1/4 or on different outputs with probability 1/2. As it turns out, this is not the case – the probability of the second option equals zero, and the photons appear on outputs only in pairs. How can we verify this? In the experiment [36], the signals from two detectors installed on the beam-splitter outputs and operating in a single photocounts mode were directed to a coincidence scheme (see Fig. 2, left). With accuracy up to technical noises, the signal from the latter turned out to be zero.

This result can theoretically be described both in the Heisenberg and the Schrödinger pictures. In the first one, the photon annihilation operators are introduced describing two plane monochromatic modes, $\hat{a}$ and $\hat{b}$. In this case, the operators of the output modes are equal to $\hat{c} = (\hat{a} + \hat{b})/\sqrt{2}$ and $\hat{d} = (\hat{a} - \hat{b})/\sqrt{2}$. Next, we find the operators of photon numbers $\hat{n}_c = \hat{c}^\dagger \hat{c}$ and $\hat{n}_d = \hat{d}^\dagger \hat{d}$, and then their correlational function $\langle \hat{n}_c \hat{n}_d \rangle$, by averaging by the original state $|1\rangle_a |1\rangle_b$. This results in ${}_a\langle 1|_b \langle 1|\hat{c}^\dagger \hat{c} \hat{d}^+ \hat{d}|1\rangle_b |1\rangle_a = 0$.

In the Schrödinger picture, we need to introduce a beam splitter matrix

$$B = \begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix} = \begin{pmatrix} \tau & -\rho \\ \rho & \tau \end{pmatrix},$$

where ρ and τ are the amplitude reflection and transmission coefficients of the beam splitter, respectively. In our case, they are equal to $1/\sqrt{2}$.

The transformation of the Fock states $|n_1\rangle$ and $|n_2\rangle$ on inputs is described by the action of the beam splitter operator [38]

$$\hat{B}|n_1, n_2\rangle = \frac{1}{\sqrt{n_1 n_2}} \times \sum_{k_1,k_2}^{n_1,n_2} C_{k_1}^{n_1} C_{k_2}^{n_2} B_{11}^{k_1} B_{12}^{k_2} B_{21}^{n_1-k_1} B_{22}^{n_2-k_2} \sqrt{(k_1+k_2)!(n_1+n_2-k_1-k_2)!}\,|k_1+k_2, n_1+n_2-k_1-k_2\rangle. \tag{5}$$

For the state $|1,1\rangle$, on the input, there are two summands with states $|1,1\rangle$ on the output, but their coefficients are identical and have opposite signs, i.e., $\tau^2|1,1\rangle - \rho^2|1,1\rangle$.

How should we interpret this result? According to [38], it can be treated as a manifestation of the wave–particle duality. Indeed, on the one hand, photons behave as particles by demonstrating single and double photocounts, while on the other hand, they seem to interfere at the beam splitter just like waves with a certain phase difference. What is this difference? Obviously, 0 or π, so that the outputs of the beam splitter would always get 2 or 0 photons. So, a certain phase difference is assumed for photons mixed at the beam splitter. Otherwise, there would be no effect of photocount correlation suppression. The presence of this phase difference is this hidden variable that completely predetermines the result of the experiment, i.e., we apparently have a hidden variable theory. Let us see now what consequences cause this interpretation.

How can we get state $|1,1\rangle$ on the beam splitter inputs? Very simple – by parametric scattering of light [39]. This was the method used in the experiment [36]. But what happens when the signal beam of the parametric process mixes with the idler beam at the beam splitter? Preparation of squeezed states of light characterized by suppression of quantum fluctuations by one quadrature at the expense of the other (see, e.g., [37] and the references therein). But is such a preparation compatible with the assumption that the signal and the idler beams must always have a phase difference of 0 or π that follows from the above-mentioned interpretation of the experiment [38] result?

We introduce the photon annihilation operators of the signal and the idler beams, $\hat{a}$ and $\hat{b}$. They are described by a Bogolubov transform of the vacuum mode operators $\hat{a}_0$ and $\hat{b}_0$,

$$\hat{a} = \mu\hat{a}_0 + \nu\hat{b}_0^\dagger, \qquad \hat{b} = \mu\hat{b}_0 + \nu\hat{a}_0^\dagger. \tag{6}$$

Then we introduce a phase delay θ in one of the channels. It is clear that this will not influence the effect of cross-correlation suppression [36] in any way. This easily follows from the above consideration in the Heisenberg picture. But how will the phase delay affect the preparation of squeezed states? We have the photon annihilation operator of a mode of one of the beam splitter outputs $\hat{c} = \dfrac{1}{\sqrt{2}}\left(\hat{a} + \hat{b}e^{i\theta}\right)$, as before. The quadrature component in this case reads $\hat{X} = \dfrac{1}{2}\left(\hat{c} + \hat{c}^\dagger\right)$. Let us find its dispersion; it is

$$_a\langle 0|_b\langle 0|\hat{X}^2|0\rangle_b|0\rangle_a = \frac{1}{8}\left(2 + \mu\nu e^{i\theta} + \mu^*\nu^* e^{-i\theta}\right) = \frac{1}{4}(1 + \mu\nu\cos\theta), \tag{7}$$

with μ and ν being real. Here, we use $|\mu|^2 + |\nu|^2 = 1$, which follows from the commutation relations $\left[\hat{a}, \hat{a}^\dagger\right] = \left[\hat{b}, \hat{b}^\dagger\right] = 1$.

So we learned that the effect of squeezing substantially depends on the phase θ. This is understandable because light on one beam splitter output is in the squeezed state, while on the other, in contrast, it possesses increased quadrature dispersion, which corresponds to a phase shift of π. But is it compatible with the assumption that the difference in the phases of the signal and the idler beams oscillates with a probability of $1/2$, taking the value 0 or π? Clearly not, because, in this case, the effect of squeezing would completely vanish by averaging. But this effect was captured experimentally (see, e.g., [40]). Thus, the main premise for the nonlocal hidden variable theory regarding the presence of a photon certain phase results in a logical contradiction that reveals its inadequacy.

One can object though that, in the experiment of photocount correlation suppression, the photon phase difference takes a different value compared to the process of registration of squeezed states, albeit the original state on inputs is the same. Such an objection would be borderline absurd, but we will attempt to disprove it formally.

We introduce a mode switch (Fig. 2, on the right) in the experiment scheme that should switch direct detection of the right detector to balanced homodyning. The latter method captures fluctuations of the quadrature field component (see, e.g., [37] and the references therein) and, if their level is lower than the level of the vacuum state, preparation of squeezed state can be stated. In the first phase of the experiment, along with capturing the effect of photon cross-correlation suppression, we register the speed of photocounts from each photodetector. Then we switch the scheme into the second mode, where the squeezed state is observed. If during this process the phase difference between photons changes from jumps between π and 0 to a constant phase difference, which is absolutely necessary for the squeezed-state preparation, then the speed of photocounts at the left detector must change as well, because at fixed phase 0 or π there will be either no photocounts at all, or their number will double. This is very unlikely to happen. It is obvious that the photocount speed will not change because, by changing the emission registration conditions from one output of the beam splitter, we cannot influence the results of registration in the other on, as it explicitly follows from the causality principle and simple quantum calculations. So the nonlocal-hidden-variable theory cannot explain this result, which renders it absolutely invalid. But if it is nevertheless correct; the photocount speed will change, although this appears extremely unlikely.

How should we then interpret the results of the experiment [36] if neither a certain phase of single photons nor their phase difference exist? Seemingly the point is that, according to the Feynman interpretation of quantum theory, it is not photons that interfere but their alternative trajectories [41]. Indeed, how is the state $|1,1\rangle$ being formed at the beam splitter output? There are two ways: either both photons are passing the beam splitter, or they both are being reflected. But, in the latter case, one of the photons is reflected by a denser medium and thus increases its phase by π. The shift phase operator $\hat{U}_\theta = \mathrm{e}^{-\mathrm{i}\theta\hat{n}}$ transforms the state $|1,1\rangle$ into the state $-|1,1\rangle$. Thus, both possible alternatives interfere in a destructive way, suppressing cross-correlations. This simple and vivid approach enables us to solve even more complex problems related to the transformation of the Fock states by a beam splitter without using the complex and cumbersome formula (5).

So the logic of our reasons is as follows.

Do the two photons in Fock state $|1,1\rangle$ have a certain phase difference (or its sine and cosine)? If so, it is the classic realism, if not, it is the quantum theory. During the process of mixing two such photons on the beam splitter in the experiment, two effects can be observed; those are the suppression of cross-correlations and the preparation of the squeezed state. We further illustrate that during a defined difference of phases these two states cannot be simultaneously present. This means that the difference of phases represents the superposition of all possible values from 0 to 2π. In this case, we do not use the locality hypothesis as everything is taking place in a single location, but we use the notion of simultaneity, which is quiet obvious. Besides, we use modeling assumptions relating to the fact that the result of interference depends on the phase difference of intermixed beams, and the effect of the quantum squeezing depends on it, and this dependence is of a certain nature, i.e., the nature resulting from the results of the experiments. To negate these model suppositions means to negate the results of the experiments. Obviously, it can be said that the effect of the cross-correlation suppression does not depend on the difference of phases, which is also proved by the experiment, but in such a case it in general cannot be explained within the terms of the classical realism unless by nonlocal phase correlation of two photons in such a way as to make the phase difference in the beam splitter always equal to 0 or π. In other words, we immediately reject classical realism or keep the possibility of nonlocal classical realism, but the latter contradicts our counterexample. Thus, there is no place for the nonlocal theory of hidden variables.

5. Conclusions

Concluding, we summarize our results.

The experiments on verification of the Bell inequalities [17–21] cannot per se prove the presence of quantum nonlocality and correlation of nonexistent measured variables a priori. Having discarded the variant of reality called local realism, we are essentially left with the following options – locality in the absence of hidden variables, quantum nonlocality in the presence of hidden variables, or nonlocality in the absence of hidden variables. The experiment we suggested (with the scheme presented in Fig. 1), it seems to us, is rather evidence in favor of the last one.

Although the theory of nonlocal realism remains one of the possible explanations of reality, our considerations (see the experiment shown in Fig. 2, as well as [23, 24]) show that the nonlocal hidden-variable theory looks rather contradictory and, in a sense, disproves itself. Therefore, the absence of hidden variables seems the most preferred option of the existence of elementary particles.

However, this leaves without answer the following question: Do measurable variables (and with a more general approach, physical reality as it is) actually not exist before a measurement (a priori), or do they exist as a superposition of all possible values defined by the quantum-system state vector? The experiment we suggest (Fig. 1), as it appears, can also answer this question well. Indeed, if a measured variable a priori did not exist at all, then a half-wave phase plate could not influence the measurement result in any way. If this does happen though, the plate obviously turns both components of the quantum superposition, i.e., changes the system state vector from (1) to (2), and this could not happen if this

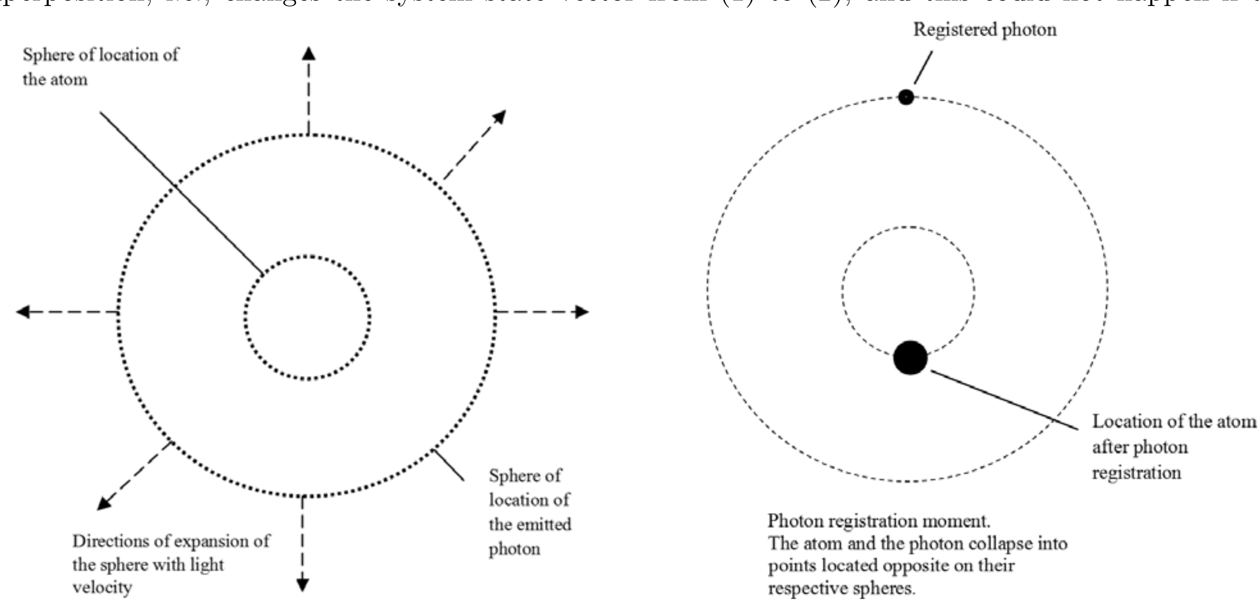

Fig. 3. The process of photon emission by a single atom in a vacuum in excited state. Until the moment of registration, the photon is located on the surface of a sphere expanding with the light velocity. According to the law of momentum conservation, the atom must also reside on the surface of a sphere of smaller radius expanding with smaller velocity. The right part shows the moment of registration when the spheres must instantly collapse into opposite points.

superposition did not exist. So, we arrive at the conclusion that the quantum-system state vector is not some virtual reality that can only serve as a part of the calculation model but represents an element of physical reality and this, in turn, shows that even quantum objects possess the status of physical reality even before the moment of their registration. In this sense, we can speak of the existence of quantum objects in the paradigm of quantum realism, unlike classical local or even nonlocal realism. The original conception of quantum realism is proposed in [42, 43].

What interpretation can be suggested to understand the phenomena described here? It is clear that the Copenhagen interpretation is not sufficient, as it does not explain anything. In fact, it only raises new questions, at the same time forbidding us to answer them. What should it be then?

We consider one more example. Let a single atom resting in vacuum in the excited state emit a photon (see Fig. 3). Should the atom experience recoil due to the law of momentum conservation? Of course, it should. But in what direction? We do not know until the photon is registered. So, the photon can be located on the surface of a sphere expanding with the light velocity. In this case, the atom will be located on the surface of a sphere of smaller radius but also expanding at a slower velocity, on the whole face, otherwise we return to the hidden variable theories. At the moment of photon registration, both these spheres will instantly collapse into (almost) points spaced opposite to one another.

If such a collapse can somewhat be explained for the photon due to its alleged field structure, this seems unreal for the atom. Before the moment of registration, the photon can propagate for an arbitrarily long time. The atom cannot possibly expand together with it. Would not it be more reasonable to explain this phenomenon as the existence of microobjects outside of space–time? In this case, the paradox of quantum effects can be explained quite rationally [44, 45].

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