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EPR: alone quantum events description

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Abstract

The obvious models of individual quantum event in the frame of EPR-experiment are considered. Along with the quantum model and the Local Realistic one a Local Indeterministic model is shortly analyzed. It is shown that any adequate EPR-model should be non-local, in this case EPR-experiment adds up to Malus-test. I propose also an explanation how the Malus law originates during individual passing of a photon through the polarizer.

Introduction

As it is known, a pair of coherent photon flies away in the opposite directions from a common space point when one tests a Bell's inequality violation in the EPR-experiment (see **[Aspect, 2000], [Weihs et al., 1998]**). There are two polarizers at each side of the setup that are separated by a spacelike distance. The coincidence counts of photons passing through both polarizers should be computed in the experiment. Note, the tests are really performed with independent photon pairs, not with some intensive photon pairs flow. This presents a specific interest because Quantum Mechanics (QM) gives the only statistical predictions for such test series.

In practice one uses the coincidence counts N_{++}, N_{+-}, N_{--}, and N_{-+} in the EPR-experiments to test Bell's inequality. For example, N_{++} is the amount of events when each of two coherent photons passed through its polarizer. Analogously, N_{+-} is the amount of events when one of photons passed through the first polarizer, and another photon did not pass through the second polarizer, etc. The total amount N of events is the sum of four coincidence counts, i.e. т.e. the total amount of the accounted coherent photon pairs. Further, the correlation function may be determined as:

$$K = (N_{++} + N_{--} – N_{+-} – N_{-+})/N = P_{++} + P_{--} – P_{+-} – P_{-+}$$

where P are respectively normalized to N event probabilities. QM predicts the following relationships:

$$P_{++}(\theta) = P_{--}(\theta) = \tfrac{1}{4}(1 + \cos 2\theta)$$

and

$$P_{+-}(\theta) = P_{-+}(\theta) = \tfrac{1}{4}(1 – \cos 2\theta),$$

where θ is the angle between two polarizer optical axis. Respectively, QM gives for correlation function:

$$K = \cos 2\theta$$

These predictions exactly correspond to the experimental data (see Fig.1).

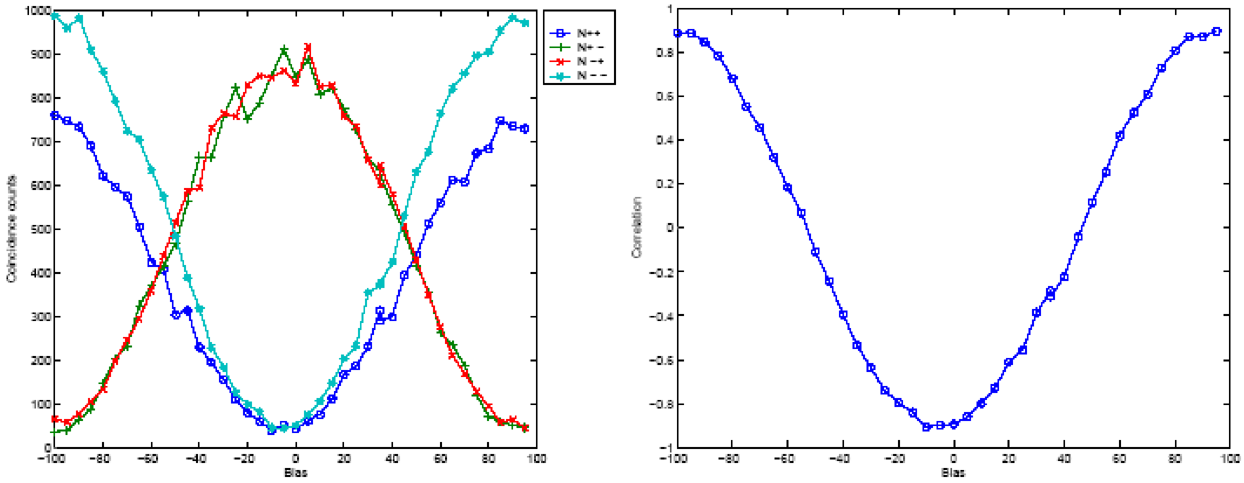

Figure 1 **[Adenier and Khrennikov, 2006]**.
Left: the coincidence counts depending on a angle difference between polarizer orientations **[Weihs et al., 1998, Innsbruck]**. Right: the correlation function

Local *deterministic* measurement models and Bell's theorem

The strong correlation between simultaneous passing of the both photon through the polarizers which is predicted by QM and confirmed be experiments leads to collision between QM and Relativity, because some "non-local influence" appears between two events that are separated by a spacelike distance. In order to overcome this collision one proposes up to now so called "hidden variables" theories. These ones deduce the correlation from some common initial cause that may generate then a coordinated behavior of two coherent photons.

In such theories one considers the common cause influence to be local (limited by a polarizer location and measurement time moment) and deterministic (i.e. completely reproducible at the same experimental setup repetition). However, as Bell's theorem states, these conditions contradict to Quantum Mechanics predictions because the Bell-Clauser-Horn-Simoni-Holt's (BCHSH) inequality should be satisfied in this case. But EPR-experiments as well as QM lead to a violation of this inequality in several cases.

I would like to note that Bell's theorem proof operates with four setup configuration and seems to be very formal. In my paper **[Shulman, 2006]** I suggested that in fact this inequality may by violated only *if the EPR-experiment result dependence on an angle θ is non-linear*, so any such theory (like QM) predicting the non-linear dependence will be incompatible with Local Realism (J. Bell's terminology). The results of my own computer simulation for such model described in **[Aspect, 2000]** are shown on the Fig.2.

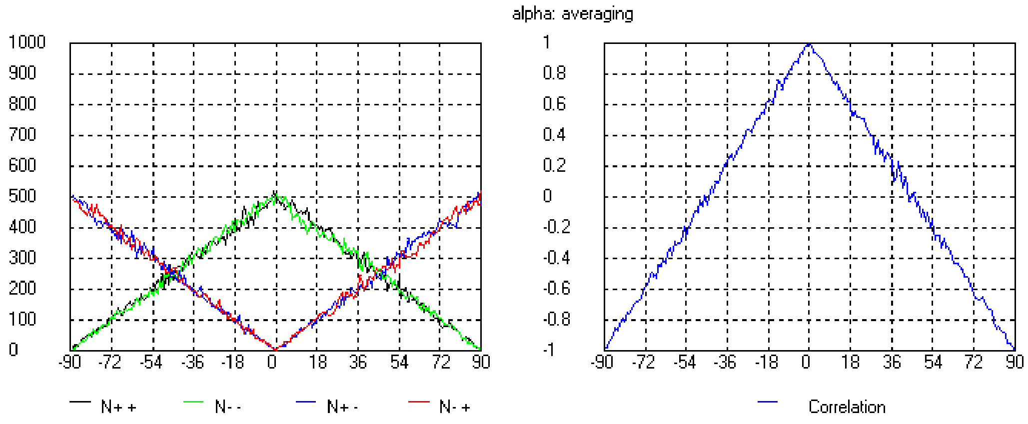

Figure 2.
EPR-experiment simulation (deterministic "naïve model) while one averages an angle between photon polarization and polarizer optical axis.

Local *indeterministic* measurement models

However, Bell's theorem says nothing on a possibility to describe EPR-experiment using an *indeterministic* measurement model of photon passing through the polarizer. Hypothetically this could explain EPR-correlations. The more, the correlation coefficient computation using standard statistical approach (i.e. *deviations from mean* and *normalization to mean root square deviation*) indeed gives K = cos 2θ that corresponds to the QM prediction. However, if one calculates the correlations of non-centerd counter values (as it is usually copmputed in real experiments), then it turns out to be two times less[1]. The analytical calculation as well as computer simulation leads to the following dependences for such model (Fig. 3):

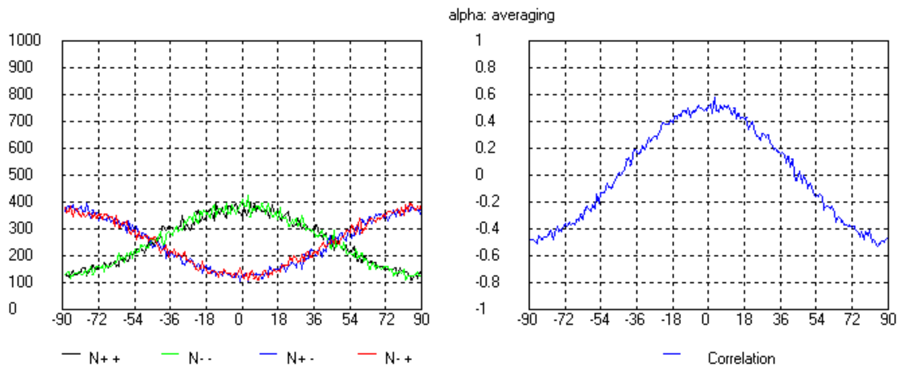

Figure 3.
EPR-experiment simulation for the indeterministic measurement model based on Malus law while one averages an angle between photon polarization and polarizer optical axis.

Two interconnected facts are very important here. Firstly, the left side of the Fig.3 shows that *the count plots lift up, so their minimal value become positive.* Secondly, the right side of the Fig.3 shows that the correlation function amplitude is only 50% relative to the QM prediction and the true experimental (100%) value. But if the correlation function amplitude was 50%, then the Bell's inequality violation was impossible.

The non-zero minimal coincidence count value contradicts to QM as well qualitatively as quantitatively. Indeed, QM predicts that the coincidence (or not) fact

[1] This is due to a non-fulfillment of the Bell's theorem condition at such normalizing procedure (see **[Belinskii and Klyshko, 1993]** , **[Barut and Meystr, 1984]**).

depends only on angle difference (θ_I – θ_{II}) between two polarizer orientations. Particularly, if this difference is equal to $\pi/2$, then the coincidence is *absolutely impossible*. Contrary, in the *indeterministic* model corresponding to the Malus law some coincidence is possible *even* if the polarizer orientations are orthogonal but a difference between "true" photon polarization λ and θ_I (or θ_{II}) is non-zero (see Fig. 4). It is just the cause of the plots lifting up on the Fig.3 (left side) when one averages over all the values λ.

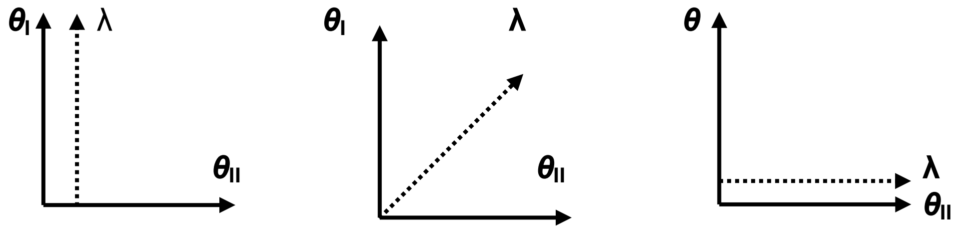

Figure 4.
Local indeterministic measurement model predictions when the polarizer axis are orthogonal.

This conclusion is enough general. If even local indeterministic measurement model was based on a law different from the Malus one, the averaging over λ followed a non-zero contribution to the minimal coincidence count values.

So, I belive that Bell's theorem treating only "realistic" measurements can be expanded up to *Generalized Bell' Statement*: ***all the local*** *(as well indeterministic as deterministic)* ***measurement models*** *are unable to describe the EPR-experiment results corresponding to QM predictions.*

Croningen "event-by-event" model

In the papers **[de Raedt et al., 2004 - 2005]** of the group from the Croningen University (Netherlands) a very interesting approach to simulate quantum events was described. It is based on the Deterministic Learning Machine (DLM) and Statistical Learning Machine (SLM) usage: when the learning sample is enough large, this model generates pseudo-statistical frequencies for alone dichotomic events with the probability equal to $\cos^2 \theta$. I simulated the proposed algorithm for single polarizer, the result completely confirmed the correspondence with Malus law. However, the key problem should be examined: how this model shows one's worth when one measures *at once two EPR-photons* – as deterministic or as indeterministic one?

The results of *my own* computer simulation were found depending on learning sample size S. They are shown on Fig.5 (S = 1) and Fig 6 (S = 100). The first case corresponds to the purely deterministic version, the second one is very close to the probabilistic version. A further sample size increasing does not practically change the dependence type excluding the especial points 90°, 180°, 270°, and 360° (their position varies up to 20%). In the both cases these simulated dependences do not correspond to the experimental data (Fig. 1) and QM prediction.

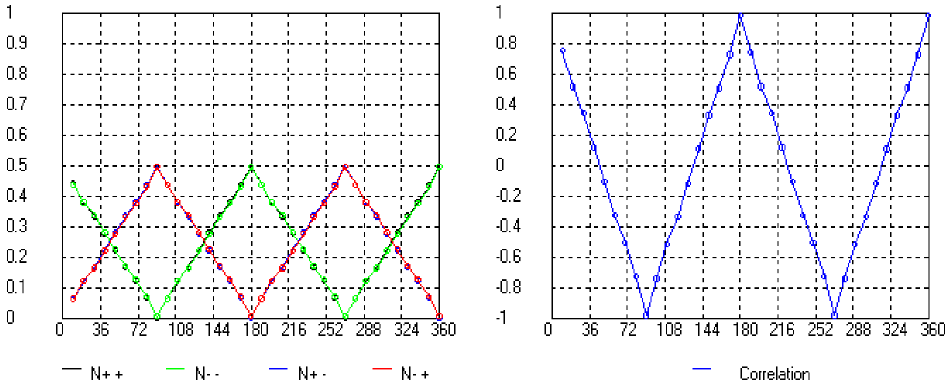

Figure 5.
My own EPR-experiment simulation based on the Croningen model
(S = 1, P_{++} min = 0, Kmax = 1)

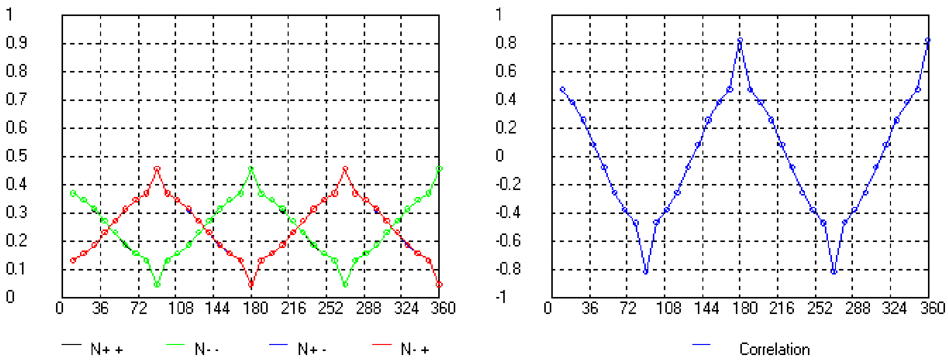

Figure 6
My own EPR-experiment simulation based on the Croningen model
(S = 100, P_{++} min = 0.05, Kmax = 0.82)

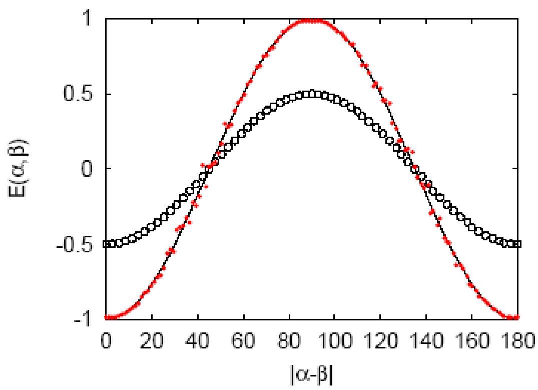

Figure 7 **[Zhao et al., 2007].**

Correlation $E(\alpha,\beta)$ between the coincidence counts as a function of the orientation difference of the two polarizers in each observation station (computer simulation). Squares (red): Simulation results using the time-delay mechanism (with d = 4) to compute the two-particle coincidence. Open circles (black): Simulation results without using the time-tags (equivalent to d = 0). Solid lines: Quantum theory.

In the recent paper **[Zhao et al., 2007]** the same authors publish their proper EPR-simulation results. As one could expect, the direct simulation gives the only 50%-amplitude of the correlation function (open black circles on Fig. 7). The authors try to overcome this fact using some time-delay mechanism to compute the two-particle coincidence and an additional “free parameter” d to fit the model. They found the coincidence with the experimental data at d = 4 (red squares on Fig. 7). However, the QM prediction (solid line on Fig.7) did not use at all any degree of freedom. So, in my opinion, such problem solution cannot be considered as satisfactory. Somehow or other a “visual” alone quantum events picture remains still absent. I propose a version of this picture in the next part of the publication.

EPR-experiment as Malus-test version

In the Malus test (Fig. 8) photons having arbitrary (or uncertain) polarization passe trough the polarizing filter P1 and *get* the polarization corresponding the polarizer optical axis (y). The second polarizer P2 optical axis (p) is rotated on some angle θ relative to the P1’s axis in the plane that is orthogonal to the motion direction z.

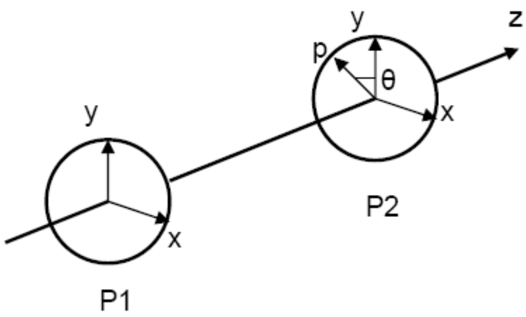

Figure 8. Malus test.

The Malus law states that in a such test the only part of the input energy can pass through the polarizer P2, this part will be proportional to $\cos^2 \theta$.

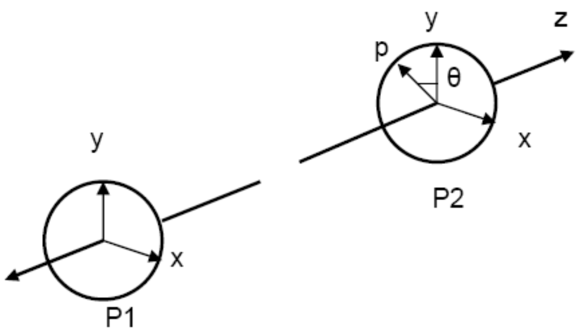

Figure 9. EPR-experiment

Let us now consider the EPR-experiment (Fig. 9). In this case the pairs of coherent photon flies away in the opposite directions from a common space point. Because of some accidental reasons one of them will arrive to its polarizer just a little earlier than another (in the reference frame where the both polarizers are immovable). So, the photon 1 was measured first and *got* the certain polarization. Further, we now *know* that the experiment is essentially *non-local*, *that is the photon 2 got synchronously the same* *polarization*. Then we just come to the Malus law version where one measures the photon 2 *after* the photon 1 has already the certain polarization. Because of that *the measurement outcome will be determined again by an angle between the polarizer axis orientations*.

As we assumed, photon 1 passes through the polarizer P1 with the probability pr(1) = ½, in this case its polarization becomes equal to y, and an angle between this one and polarizer P2 optical axis becomes equal to θ. We also know that QM gives for joint probability the both photons 1 and 2 to pass through the polarizers P1 and P2 the value $pr(2) = ½ \cos^2 θ$. In other words, it may be written as pr(2) = pr(1)·pr(θ), where the *conditional probability* $pr(θ) = \cos^2 θ$ exactly corresponds with Malus law.

How Malus law may appear during alone event

The most interesting consists in an obvious model creating where a dichotomic outcome (does photon passed through a polarizer or not) is determined by Malus law ($\cos^2 θ$). How *each alone photon "knows"* with which probability an outcome should be chosen? I propose my own answer this question.

Let us correspond a traveling wave to every photon. Although a photon has constant energy it presents the sum of two oscillating terms – electrical and magnetic. Each photon that passes through the polarizer has some (random) phase at the "meeting" moment, i.e. some accidental instant electrical field energy.

As it is known, when a wave comes to a "grid" consisting in the long polarizer molecules, the reflected wave appears that "inhibits" the incoming one. This reflected wave amplitude will be equal to cos θ relative to the incoming wave amplitude. Hence, the power "threshold" will be equal to $\cos^2 θ$. If instant value of the photon electrical energy will overcome this threshold, the photon will pass the polarizer.

Conclusion

The obvious models of individual quantum event in the frame of EPR-experiment are considered in the paper. Along with the quantum model and the Local Realistic one a Local Indeterministic model is shortly analyzed. It is shown that any adequate EPR-model should be non-local, in this case EPR-experiment adds up to Malus-test. I propose also an explanation how the Malus law originates during individual passing of a photon through the polarizer.

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