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Non-Locality, Duality, and “Invisible” Photons

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Abstract

The fundamental representations of quantum mechanics such as non-locality and the duality “wave-particle” are discussed. I consider the interaction properties in an EPR-experiment where a correlation exists, but an information transfer is interdict. The wave-like features of quantum mechanics are associated with wave-like ones of a single elementary particle field. I propose the “threshold hypothesis” that replaces a quantum randomness by a classical one that depends on the non-local hidden variable (particle phase) at the measurement.

EPR-experiment as a version of Malus experiment

The known Malus rule describes the following experiment (Fig. 1): the photons having random polarization after they transverse polarizing filter P1 *get* the polarization corresponding to its optical axis (y). The optical axis (p) of second polarizer P2 is rotated on some angle θ relative polarizer axis of P1 in the plan that is perpendicular to the motion direction z.

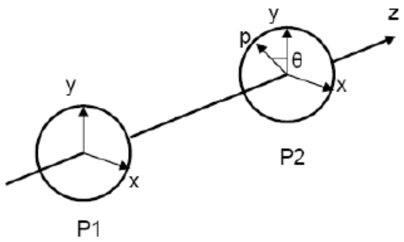

Figure 1. Malus-experiment

The Malus rule states that in such the experiment the only part of the input field energy flow can transverse the polarizer (в частности, монохромного), and that relative photons fraction will be proportional to $\cos^2\theta$, where θ is the angle between the optical axes of P1 and P2. Correspondingly, the remain part of the photons that were not passed P2 will be proportional to $\sin^2\theta$.

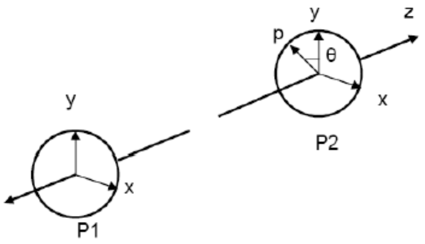

Figure 2. EPR-experiment

Let us now consider an EPR-experiment (see, for example, **[Aspect, 2000]**), that is shown on the Fig. 2. There a pair of *entangled* photons fly away from a common point to opposite directions. It turns out that one can consider qualitatively and quantitatively this experiment as the Malus experiment (see **[Belnsky, 2008]**). First photon that comes to the filter P1 is like the *herald* photon triggering a *window of exposition* of some duration (similarly to experiments of **[Grangier, 1986]**). Then the EPR-experiment is reduced to the counting of the second photon detection at the filter P2 during the corresponding window. Because of that the *experiment outcome will be determined by the angle* between polarizer optical axes, so the detection coincidence fraction will be proportional to $\cos^2\theta$, and the remain fraction will be proportional to $\sin^2\theta$.

On non-local interactions

In the above experiments the polarization angle difference $\theta = \theta_1 - \theta_2$ of two distant detectors is a global feature of the domain containing considered two-photon entangled state and has to be considered as *non-local* parameter. Accordingly, EPR-experimens show **[Salart et al., 2008]** that the angle of each polarizer can be modified at any time, just at a last instant before a measurement. The angle difference θ will be modified too at the same time.

One usually discuss the superluminal communication possibility between the points 1 and 2. However, in my opinion *we don't need at all* in such the communication. Let us denote a sudden jump of the P1 polarization angle as $\Delta\theta$. It is clear **[Shulman, 2006]** that $(\Delta\theta + \theta_1) - \theta_2 = \Delta\theta + (\theta_1 - \theta_2)$, i.e., the angle difference at the same time will automatically change on the same value $\Delta\theta$. However, this formal adding operation has to be ensured by some *physical* structure like considered entangled two-photon state. In fact, mathematically this result is true for *any* spatial domain, however, the only real existence of the two photons entangled domain made it the physically sensible one. This domain practically plays the role of some incompressible bar. However, though the Special Relativity, as one believes, interdicts the such bar existence because during the motion its length decreases due to Lorentz transformation, however, in this case the bar (the photons that compose it) moves vith the velocity of light in *any* reference frame, so its length does not change in any reference frame too.

Do the detectors P1 and P2 interact between them? Usually one associates an interaction with an energy exchange. When the energy certainly transfers from the point 1 to the point 2, the action for this process is not equal to zero, the 4-distance between 1 and 2 is time-like one. Contrary, at the inverse process the same energy transfers from the point 2 to the point 1, the action and 4-distance change their sign. However, the itermediate case is possible when *on an average* the transferring energy is equal to zero, so the enegy and information *do not transfer*. But it is possible (if such two events are physically linked, for instance, by above incompressible bar) that the *root mean square is not equal to zero* (like vacuum zero fluctuations leading to the Lamb shift). This is the genuine cause of a correlation without an information exchange.

Wave-like quantum behaviour and superposition state

We may say that in the both Malus-experiment and EPR-experiment one can decompose the measured state of photon $|c\rangle$ in a 2-dimensional orthogonal base $\{|a\rangle, |b\rangle\}$ in the Hilbert space. This measured state is a superposition of basic states and may be specified by an angle θ with basic vectors:

$$|c\rangle = \cos\theta|a\rangle + \sin\theta|b\rangle$$

Correspondingly, this state projections can be expressed via sine and cosine of this angle (in this case – between filter polarization axes).

Many years before Niels Bohr formulated the famous principle of complementarity. He stated that quantitatively a quantum object in one experiment behaves like particle and in another one like wave (no like the both types). However, the modern picure based on the numerous experiments allowed us to precise this principle. Even in the same experiment one may introduce two parameters: the interference (*visibility*) V that specifies the wave-like behavior and particle path *distinguishability* D that describes the particle-like features. Note, that ideally $V^2 + D^2 = 1$. Particularly, in the work **[Jacques et al., 2008]** this issue was tested in the experiments with Mach–Zehnder interferometer: the measured values of V and D satisfy the condition $V^2 + D^2 \leq 1$. Again, these values V^2 and D^2 can be associated with squares of sine and cosine of the angle between the state and basic states.

The sine and cosine components together describe a harmonic wave of the harmonic linear oscillator. Such the oscillator *without energy's loss* has a phase shift $\theta = \pm\pi/2$ between the (generalized) coordinate and (generalized) momentum. In this case all the oscillations energy in the system is *reactive* and does not leave the system. However, if the oscillator has an energy loss (for example, in an electric circuit that contains also a resistor, not only the capacity and inductance), then above phase shift θ *differs* from π/2, so the full energy contains also an *active* component that irreversibly leaves the system over the period. Because of that one usually considers the harmonic system full energy as a *complex* value that generally includes two components: real (active) part and imaginary (reactive) one.

The link between a wave and particle turns out to be more transparent if we remarked that the particle *amount* (detected per a time period) corresponds to the transported *active* (real) power that is proportional to the square of cosine θ[1]. But this means that one may introduce the *full* particle amount that corresponds to the full (complex) power. If so, then the *reactive* (imaginary) fraction of the particle amount that is *not detected* by detectors exists too. Due to this when one varies the difference θ of the polarization angles in an EPR-experiment the *full* particle amount does not change, but it is redistributed, so the sum of the detected and non-detected particles remains *constant*.

Photon as a wave. The "threshold hypothesis"

Why do the sine and cosine components play such the role? One may believe that the wave-like features are born on the level of elementary quantum particles (photons, electron, etc.) In fact, when one describes for example a photon in the frame of quantum optics, one transits from a field complex amplitude to so-called quadratures. One of them corresponds to the field generalized *coordinate*, while another corresponds to the field generalized *momentum*. Accordingly, the first one corresponds to the potential energy, while the second one corresponds to the kinetic energy of the electromagnetic oscillator. Their total sum is a constant over time while each of them *oscillates* (just like to the case of a mechanical oscillator). Therefore, when we say "generally" about the photons identity, we have to

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[1] Finally we come to the famous Born rule: the probability density to find a particle is proportional to $|\psi\psi^*|$. The angular parameter θ is equal to the phase shift between the (generalized) coordinate (for example, electric field strength) and (generalized) momentum (for example, magnetic field strength) for oscillating field of a particle.

understand that each photon at one time point differ from the same photon at another time point. Such the difference is associated with a *phase* of electromagnetic field oscillations that the photon transports.

The phase is, as I believe, the true “hidden variable” in the Bell’s and von Neumann’s sense. The standard quantum theory refuses any *local* hidden parameter existence, and all quantum events are considered as “truly” random ones. However, in the numerous works the idea was stated that the relative phase of a wave function partial term may play the role of a *non-local* hidden variable and even may be experimentally measured in principle (see for example **[Peil, 2013]**), since the Bell’s theorem *does not interdict* such the possibility.

So, the detection (or non-detection) of the particle by a detector depends unambiguously on the (random) phase value at what the particle meet the detector. The detector registers a particle that gives it its *active* energy. If this particle is a harmonic oscillator, then its *full* energy (as I mentioned above) can be represented as a *complex* value. The real component depends on a (generalized) momentum, it is an *active* energy that can be *irreversibly* transferred the energy from one system to another, can transport the information, can transformed to the heat, etc. The imaginary component corresponds to the potential energy that depends on a (generalized) coordinate. It is the *reactive* energy that is associated with a strongly *reversible* oscillating process[2].

Then one can propose the following “threshold hypothesis”. A detector will click if the *kinetic* (not full!) energy of the elementary single oscillator (photon) is bigger than some threshold level that depends on above angle θ (that is non-local parameter). Let us consider this question in detail.

The photon’s energy is determined by the known relation $E=\hbar\nu$, and the modulo of the associated field amplitude is equal to the square root of the energy. The oscillation phase of the momentum is shifted relative the coordinate phase. The kinetic energy is *bigger* than some threshold level when the potential energy is (contrary) l*ess* than the corresponding threshold. An angle θ specifies some *spatial* direction of the coordinate oscillation. Because of that, if this the coordinate oscillates as sin ωt, then we integrate from θ up to (– θ) and find that such the threshold for the momentum has to be proportional to cos θ, and for the needed kinetic energy it has be proportional to $\cos^2\theta$.

When we deal with a polarization experiment (Malus, EPR), this angle θ is equal to the differences between two polarizing detector axes and determines a relation between the transmitted and reflected photon fraction.

When we consider the processes in a *non-linear* beam splitter, the “threshold hypothesis” has some indirect evidence. The Heisenberg’s uncertainty principle is automatically satisfied in such the *quantum* beam splitter, since a variance of the beam splitter transmissivity leads to the correlated output amplitude variance and synchronously to anti-correlating variance of the output beam phase. However, the similar *classic* model **[Belinsky, 2011]** does not indicate to such the anti-correlation (as well as any correlation). But if the described hypothesis is correct, then (as we have above seen) the amplitude and phase selection of transmitted photon *is not random one*, it is linked with the parameter θ, so the amplitude and phase should anti-correlate as the uncertainty principle dictates.

When we move from a large particle amount to a single particle experiment another reason appears. The photon number decreasing once leads to the situation, when a single particle (e.g., a photon) has to “split” or behave *randomly*. But from where the photon “knows” the probability that determines its choice? The explanation that the threshold

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[2] However, a transition between these energy forms is possible, for example: a capacity charge from an energy source, or a capacity discharge through a resistor.

hypothesis gives is that each time a random electromagnetic field oscillation phase of the particle is compared with the *non-local* parameter θ. Of cause, the non-local parameter value will be violated if an attempt to observe the particle trajectory is made.

“Invisible” photons

Let us consider one more important theme. The following experiment with the Mach-Zhender interferometer (Fig. 3) is well known. This interferometer contains two beam splitters (B1, B2) and two mirrors (M). As the *corpuscular* theory predicts, the output photons are detected by the detectors D1 and D2 with the equal probability. However, the *wave* theory and quantum mechanics predict another result that corresponds to the reality (see for example **[DeWeerd, 2001]**). Particularly, if the optical lengths of both lower and higher arms of the interferometer are equal and the first beam splitter reflectivity is equal to second beam splitter transmissivity, then the photon that incomes into the interferometer from below will always detected by D1 and never by D2.

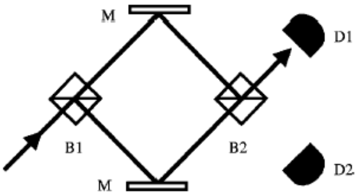

Figure 3. Mach-Zhender interferometer (**[DeWeerd, 2001]**)

In fact, the wave-like description takes into account the photon *phase*. A wave that falls onto the output D2 consists of two components having the same amplitude, but the opposite phase, so the total wave amplitude coming into D2 is always equal to zero. Similarly, two waves emitted by different sources on a water surface may mutually liquidate one another in several points due to interference[3].

But what the absence of the photons in the points within zeroth total wave amplitude does it mean? In the naïve version the question is: where the photon “disappear”? The standard quantum mechanics hasn’t some answer. However, the mentioned above threshold hypothesis allows us propose another answer: the photons do not disappear near detector D2, but *are not detected* by it because their active energy component is always zero in this point due to the interferometer configuration and cannot be used by a detector in order to the signal receiving. It means that any information cannot be transmitted from the interferometer input to the point D2. Hence, not only spatial-like separation can interdict the one-directional energy and information transmittion between two points.

Appendix

About one attempt to disprove the EPR-paradox

So far one knows a number of the attempts to disprove theoretically the Bell’s theorem and the Einstein-Podolsky-Rosen’s (EPR) paradox existence. Particularly, prof. W. Hofer (since 1990s) regularly publishes his solution where he revised several Quantum Mechanics

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[3] Note, generally an interference leads to the particle “partial disappearance” (as, for example, in the famous two-slit experiment).

standard statements. His prove of the Bell's theorem falsity is just connected with my above consideration, so I am going in turn to criticize the prof. Hofer's concept (see, for example, **[Hofer, 2011]**).

Dr. Hofer uses for each of the flying away photons of the EPR-pair the complex wave function like $R(\varphi) = \exp^{i\varphi}$, where φ is a measured (random) value of the corresponding photon polarization angle at the detection point.

Then one has the probabilities to detect first and second photon correspondingly:

$$p(\varphi_1) = \{\mathrm{Re}[R(\varphi_1)]\}^2, \quad p(\varphi_2) = \{\mathrm{Re}[R(\varphi_2)]\}^2.$$

So, the each independent measurement probability is the *real part* square of its wave function. Further, one usually calculates the joint probability as the product:

$$p(\varphi_1, \varphi_2) = \{\mathrm{Re}[R(\varphi_1)] \cdot \mathrm{Re}[R(\varphi_2)]\}^2$$

However, Dr. Hofer proposes to use another relationship:

$$p_H(\varphi_1, \varphi_2) = \{\mathrm{Re}[R(\varphi_1) \cdot R(\varphi_2)]\}^2$$

Thus, he uses the *real part of the* (complex) *product* besides the *product of the real parts*! In this case only one can come to the correct value of the correlation:

$$p_H(\varphi_1, \varphi_2) = \cos^2(\varphi_1 - \varphi_2 - \Delta)$$

However, in my opinion, such the replacement can be correct only if the measurements at the points 1 and 2 are performed on the physically *single* object (not on two independent ones), i.e., at the edges of the “absolutely incompressible bar” that is represented by the non-local pair of the EPR-photons.

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