Quantum nonlocality.

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Abstract: Experiments with entangled particles and various interpretations of the experiments are usually combined under a common term 'Quantum Nonlocality'. This work analyzes the term ‘nonlocality’ and gives a brief overview of the known interpretations of the entangled particles paradox. A model of the physical vacuum as a superfluid is proposed. Structures forming in the superfluid physical vacuum that surround a particle can give an explanation of the quantum entanglement phenomenon.

Keywords: entangled particles, quantum nonlocality, superfluid physical vacuum.

1. Entangled particles.

The probabilistic interpretation of quantum mechanics encounters paradoxes which still do not have a definite explanation. One of them is the paradox of **the entangled particles.** The quantum state of each entangled particle cannot be described independently of the state of the other even when the particles are separated by large distances. Because of that the probabilistic interpretation leads to peculiar correlations between systems in an entangled state. This was demonstrated by David Bohm in 1951 with the following thought experiment.

A pair of particles is emitted from the same source in the so-called spin singlet state (the total spin of the pair is zero) . The particles travel in opposite directions and each encounters a measuring apparatus that is set to measure their spin components along various directions.

According to the quantum formalism, the measurement outcomes must be correlated even for measuring events that are a large distant from each other. If, for example, one particle has spin 1/2 along the z-axis, the other particle must have spin in the opposite direction along this axis. If one changes the direction of the measurement from z- to x- axis for the first particle, then the second particle, must have spin in the opposite direction along the x- axis. Note, that each individual measurement produces random results for one particle. Surprisingly, these random results turn out to be in correlation with the results of similar measurements performed on another particle from the entangled pair.

Correlations between the entangled particles' characteristics have been confirmed experimentally (the so-called Bell tests). These correlations have interesting properties: (1) they are independent of distance; (2) these correlations have a property of selectivity; that is, only those particles which are originally described by a common wave function retain the quantum correlation, and (3) quantum correlations do not require energy. These peculiar correlations between systems in an entangled state led many scientists to think about incompleteness of the description of physical reality by quantum mechanics. Albert Einstein, Boris Podolsky, and Nathan Rosen addressed this problem in an article "Can quantum mechanical description of physical reality be considered complete?" that was published in 1935.

In 1932 John von Neuman raised - and he was probably the first - the problem of 'hidden variables'. 'Hidden variables' are some, not yet explored, properties of elementary particles, that would allow a quantum system's consistency with the deterministic theory of elementary particles. Neumann proved mathematically that any hidden variable theory would be incompatible with the main principles of quantum mechanics. However, it was later shown that Neumann did not take into consideration a class of *nonlocal hidden-variable theories* in his proof[1] De Broglie was the first who noticed this: when he got familiar with von Neumann's work, he said that the very existence of the pilot-wave theory indicates a weakness in Neumann' reasoning. It also follows from Neumann's proof, that introduction of a *local hidden-variable* in quantum mechanics would mean abandonment of the probabilistic interpretation and transition to a causal interpretation of quantum phenomena.

2. Nonlocality

What is meant by 'nonlocality '? 'Nonlocality' may refer to phenomena which exhibit the ability of objects to either (1) influence each other's state instantaneously, even when they are separated at large distances or (2) influence each other's state by means of a signal propagating at superluminal speed. The scientific models (theories) in which nonlocality is implied are called 'nonlocal'. It makes sense to separate nonlocal classical theories from quantum nonlocality. Examples of the *classical nonlocal theories* include:

1. Newtonian gravitational theory, which has ***action at a distance*** postulated in it, and therefore, is a nonlocal scientific model. From the perspective of this theory, the force of gravity does not "propagate" continuously from one mass to another in space but acts instantaneously

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[1] Einstein's condition of locality: if two systems no longer interact with each other during the measurement, then no operations on system one can cause changes in system two.

2. The models which imply ***'instantaneous interaction between distant particles of a medium".*** An example of such a model is the model of an ideal incompressible fluid. Small changes at the boundary instantly result in the pressure change throughout the entire volume of the fluid, that is, a pressure in the ideal incompressible fluid is transmitted instantaneously. The ***instantaneousness*** here is a part of the physical model. Real fluids are always a little compressible. Small changes at the boundary produce a pressure wave, called a "precursor", that propagates through the fluid with large but finite speeds.
3. De Broglie–Bohm's theory, also known as the pilot-wave theory is another example of a nonlocal model. The velocity of a particle in this model is defined by Hamilton's principal function, which in turn, is defined by a wave function. The wave function depends on the boundary conditions of the system, therefore, any changes on the boundary *immediately* affect the velocity of the particle.
4. 'Nonlocal' is also any theory involving media wherein disturbances can spread at speeds greater than the speed of light**.** Such theories, obviously**,** contradict the theory of relativity (TR) since TR only allows propagation of energy at sub-light speeds.

Generally speaking, any theory which assumes existence of an 'action at a distance', or 'an instantaneous connection between distant particles' is inconsistent with the theory of relativity. TR contains a hidden postulate of locality, which states that an object is directly influenced only by its immediate surroundings.

Experiments with entangled particles and the theories that offer interpretations of the phenomena are usually combined under a common term **'Quantum Nonlocality'**. The theories themselves, however, are not necessarily nonlocal. For example, the theory which explains the experiments with entangled particles in terms of *the quantum non-separability*[2] is local.

3. **Bell's inequalities.**

In 1964 John S. Bell proposed his famous inequalities. All minimally reasonable classical statistical models satisfy these inequalities; however, quantum models violate these inequalities. Klyshko D.N. et al. analyzed **various interpretations**

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[2] Followers of the theory of quantum non-separability suggest that some type of an information "link" exists between remote quantum objects. That is, quantum mechanics is a non-separable but local theory. Note, that separability means that spatially separated systems exist in states that are independent of each other. Locality means that the state of the system can only be modified by means of interactions that propagate at sub-light speeds. Theidea of non-separability of the Universe agrees with the philosophical concept that the Universe cannot be divided into separately existing "elements of reality" in such a way that each of these elements has its own mathematical description. In other words, a system cannot be analyzed into parts whose basic properties do not depend on the state of the whole system.

of these violations for the case of entangled particles [1], and proposed three possible mathematical approaches to the entangled particles problem: (1) remaining within the concept of existence of the joint probabilities to introduce unknown superluminal forces between the measuring devices or between entangled particles; (2) remaining within the concept of the existence of the joint probabilities, to introduce negative probabilities; (3) rejecting the joint probabilities and, consequently, rejecting the assignment of any a priori properties corresponding to non-commuting operators to quantum objects. Consider each of these approaches.

1.) *Joint probabilities plus 'superluminal forces'.*

Let us assume that quantum objects have a priori (before the measurement) defined properties corresponding to non-commuting operators, but it is impossible to measure those properties simultaneously. For example, a source emits polarized correlated photons that are detected by two receivers, A and B, containing polarizing prisms and detectors. We assume that the polarization of each photon is known a priori. Measurements of the polarizations at A and B lead us to the conclusion that the orientation of a prism which is located at point A influences the readings at point B, and the orientation of a prism in B influences the readings of the detector at point A (or that the detection of the photon at A leads to a change in the properties of the photon at B before the measurement and vice versa). In theory, each of the photons could be emitted in opposite directions. In which case the quantum correlations would mean that unknown 'superluminal forces' act between the remote measurement devices at A and B (or between the photons). In other words, if we assume that quantum objects have a priori defined properties corresponding to a non-commuting operator, we must introduce hypothetical entities (some type of nonlocal hidden variables) into the quantum theory, which would provide an explanation of these peculiar correlations.

Notice that if we assume the existence of superluminal interactions, then the quantum theory would be inconsistent with special relativity.

2.) *Joint probabilities plus possibility of their negative values.*

The inequalities of the Bell type can be formally satisfied in some cases if we add negative (or even complex) joint probabilities to quantum theory. For the first time negative probabilities were introduced by Paul Dirac in 1942 in his article "The Physical Interpretation of Quantum Mechanics". Within the concept of negative probabilities some of Kolmogorov's axioms of the probability theory do not work.

It is shown in some works (for example in the work by Belinski A.V [2]) that if one assumes that quantum objects have a priori property (corresponding to non-commuting operators), then the negative values of joint probabilities in description of an experimental result have the following meaning: a change in a receiver would mean the very properties of the quantum objects had changed.

3.) ***Rejecting the concept of joint probabilities and, consequently, the possibility of ascribing a priori properties corresponding to non-commuting operators to quantum objects.***

Around 1927 while working together in Copenhagen Niels Bohr and Werner Heisenberg formulated so-called 'Copenhagen interpretation of quantum mechanics', which was widely accepted and remains so until today. According to this interpretation a particle does not possess any definite properties prior to a measurement, and questions, such as 'where was a particle before it was detected by a device' make, therefore, no sense. Followers of the Copenhagen school insist that quantum mechanics deals only with probabilities of observed quantities and measurements. In their view, joint probabilities of non-commuting operators cannot be used because direct measurement experiments cannot be conducted.

In the Copenhagen interpretation the wave function, which describes superposition of possible quantum states, exists at all points simultaneously. The spin of the first particle and the spin of the second particle in Bohm's thought experiment which we discussed above, according to this interpretation, are not independent quantities. Therefore, no distant communication is taking place. At the instant a measurement of the first particle is made, an immediate change in description of the system's quantum state occurs. The entire wave function collapses into a single state. The probability density at the collapse disappears simultaneously everywhere except for the location where the system is detected. The non-locality here manifests itself in this collapse.

It is obvious that the Copenhagen interpretation contradicts the idea of 'local realism'. From the point of view of local realism, all characteristics of the object of study must have objectively existing values regardless of measurements. The Copenhagen interpretation, on the contrary, allows elements of 'magic'. Note, that although some properties of entangled particles exist only potentially before a measurement, there is a correlation between them.

The success of the Copenhagen interpretation is in providing a working algorithm for prediction of quantum system behavior. However, it offers little explanation of the nature of quantum processes and causations in the quantum realm.

4. **Hidden-variable theories.**

Many physicists have come to terms with existence of some processes in quantum physics that cannot be explained in an intuitively clear way. Supporters of the hidden-variable theories, however, believe that paradoxes that are observed in quantum measurements are due to the incompleteness of our knowledge of the microworld. For example, the correlation between *entangled particles* can be explained if we assume that each of the *entangled particles* carries all the information with it. If that is the case, then each particle of the *entangled particles* must have a complex structure capable of storing information. This information is carried with the particle, and therefore, propagates continuously from point to point in space. We do not need to introduce in this case a superluminal interaction between the particles.

The Stern–Gerlach experiment supports this hypothesis, as it demonstrates that a particle stores 'memory' about the spin it previously had.

In the Stern–Gerlach experiment a beam of electrically neutral particles such as silver atoms pass through an inhomogeneous (spatially varying) magnetic field [Fig. 1]. Due to the inhomogeneous field the particles with nonzero magnetic moments deflect, and, contrary to continuous distribution that would be expected from classical spinning object, they deflect either up or down at a specific distance. The Stern–Gerlach experiment was the first experiment that demosntrated that the spatial orientation of the particle’s angular momentum (a spin) is quantized . This experiment was later repeated for free electrons [3].

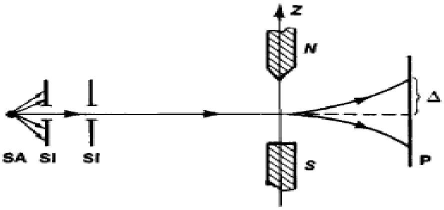

Fig. 1 Stern–Gerlach experiment. Due to an inhomogeneous field particles deflect either up or down at a specific distance [3]

Let us consider a more complex experiment in which we link two identical S-G apparatuses. If after the first S-G apparatus we place a blocker such that only particles with spin up can enter the second S-G apparatus, then at the output of the second S-G apparatus only particles with spin up are detected (Fig. 2). This result is not very trivial. It demonstrates that a free particle is capable of storing 'memory' of the direction of its spin. Recall that, in principle, it is impossible to measure a free particle's spin as it interacts with magnetic field during the measurement, and, therefore, is no longer free. Theoretically a free

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[3] Image by https://encyclopedia2.thefreedictionary.com/Stern-Gerlach+Experiment

particle does not possess a definite spin between the S-G apparatuses before the measurement. We cannot even claim that it has a spin at all.

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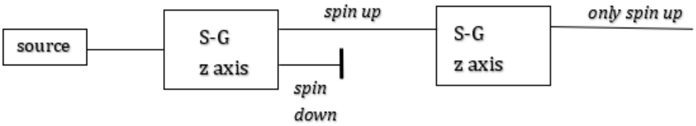

Fig. 2 The Stern–Gerlach experiment with two apparatus

A good question to raise is how long the particle can store a 'memory' about the spin that it previously had. In other words, how stable is this process? The answer to this question can be found in the results of the following experiment.

Let us incline the z axis of the second S-G apparatus at angle θ. For a small θ most of the particles demonstrate a spin projection upward along the new z′ axis in the output of the second apparatus, and a small number of particles show spin downward along the z′ axis. The larger the angle θ, the more particles will have spin downward. For θ = 90° the number of both particles having spin in one direction and another direction will be statistically almost equal.

Assume that alongside the S-G apparatus that allows only spin up particles, we place another independent S-G apparatus that allows only spin down particles. As follows from the experiment, particles are capable of retaining information about their spin orientation for long time. It is obvious, that if one particle leaves the first S-G apparatus with spin up, and another particle leaves the second S-G apparatus with spin down and the particles traveled away from each other to large distances, then when their spins are measured, they will show spin up and spin down correspondingly. We do not need to introduce any superluminal interactions between the particles to explain the results of these measurements.

Let us go back to the problem of entangled particles. According to the modern view, a particle from a pair of particles in a unified quantum state with zero total spin, does not have a definite projection of spin in any direction. The particles demonstrate opposite orientations only at the moment of measurement. If we use the concept of 'hidden variables' to approach this problem and search for the causal interpretation of the entangled particles experiments, we can conclude that each particle has a preferred projection of its potential spin along any direction before the measurement. Then a question arises how do particles become entangled?

4.1 *A cloud of soft photons accompanying a particle can provide an explanation to the quantum entanglement* **phenomenon** (*D.A. Slavnov's model)*

D.A. Slavnov proposes in [4] an answer to the above question. His theory aims to bring into agreement the theory of relativity and quantum non-locality, with the help of quantum field theory. According to the quantum field theory a cloud of soft photons appears around a particle during scattering. The energies of the soft photons' are much smaller than the energies of the particles participating in the process.

According to Slavnov's theory there is coherence among the photons in the cloud, as well as between the photons and the particle. The idea of a cloud of soft coherent photons surrounding a quantum particle is in good agreement with the idea of de Broglie's wave reality. However, unlike de Broglie's pilot wave, the cloud of coherent photons does not imply presence of any kind of medium.

In the case of *entangled particles*, correlation between two subsystems, each of which consists of a particle and a cloud of soft photons, appears as the *entangled particles* are born. Correlation is preserved when the subsystems disperse to large distances. Note, that when we talk about quantum correlated systems, by correlation we mean the correlation between the results of the measuring devices. Interaction of one subsystem with a measuring device does not affect the results of the measurements on the second subsystem. All we obtain from measurements of the first subsystem are the instructions on how to collect statistics for the study of the second subsystem.

Thus, according to Slavnov, if we assume that a cloud of soft coherent photons surrounding a quantum particle exists, then we **do not need to introduce non-locality to explain the results of the experiments with the *entangled particles*** and can remain within the framework of a local scientific model.

Summary. For the solution of the entangled particles paradox, Slavnov uses elements of the quantum filed theory. The soft photons accompanying a particle take on the role of local hidden variables in his theory. Thus, Slavnov's theory is a local hidden-variable theory.

Some parts of Slavnov's theory remain unclear. For example, what is the nature of the particle – cloud coherence? Also, the soft photons theoretically appear during scattering, so why does the cloud continue to accompany the particle when it moves at a constant velocity? If that is the case, that would mean that new soft photons must continue to be born during the particle's motion. Besides that, how would Slavnov's model work in the case of entangled photons?

However, what is new in this theory is the existence of a cloud of elementary particles (the soft photons) accompanying a particle. The *quantum entanglement* between particles occurs when the clouds of elementary particles interfere, or, strictly speaking, when the particles are in a common, unified quantum state.

4.2 *A structure forming in the superfluid physical vacuum surrounding a particle can give an explanation to the quantum entanglement phenomenon (Sotina's hypothesis)*

The quantum field theory combines the elements of quantum mechanics with those of the theory of relativity (TR). The physical vacuum in TR has a uniform energy density everywhere and, therefore, spatial structures cannot exist in such a vacuum. Indeed, if spatial structures existed in the physical vacuum, then it would be possible to link a coordinate system with a structure. It would make it possible to introduce an "absolute motion" for objects with respect to this coordinate system. This is in contradiction to the postulate of Special Relativity – the postulate of relativity.

If we move away from the model of 4-dimensional space-time of TR and work within the model of the three-dimensional Euclidean space and independent time, we can model the physical vacuum as a type of medium where spatial structures can form. We believe in this regard, that a medium similar to superfluid ^{3}He is most suitable for this role [5, 6, 7]. The superfluid properties of vacuum (zero viscosity while in motion) would explain the observed non-dissipative motion of bodies in space. The presence of electrically unlike microparticles in vacuum would describe its dielectric properties.

At low temperatures ^{3}He transits to a Bose-condensate state. In this case, individual molecules of helium-3 are combined into pairs similar to Cooper pairs of electrons. Superfluid ^{3}He-B consists of pairs of fermions with singlet pairing, ^{3}He-A is a spin-polarized ^{3}He phase. The superfluid ^{3}He-A provides many examples of topologically stable defects (spin structures). For example, a homogeneously precessing domain [8]. Another object that is observed in ^{3}He-A is a vortex that ends with a 'spin hedgehog' (the Barnett effect in superfluid ^{3}He leads to a possibility of generating vortices that terminate in the superfluid due to the complete transfer of the vortex angular momentum to the orbital angular momenta and spins of the particles constituting the vortex) [9]. The angular momentum of the vortices observed in the superfluid ^{3}He are quantized.

If the physical vacuum is like the superfluid ^{3}He then a spatial spin structure must surround a particle. In an external field the structure aligns along the field and forms a vortex with quantized angular momentum - a spin. If two particles are surrounded by such structures each of which consists of the vacuum micro-particles having oppositely oriented spins, then in the presence of an external field they form vortices with opposite spins. If now these two particles are separated, then when measured they will behave like the entangled particles in the spin singlet state.

The hypothesis about structures forming in the superfluid physical vacuum surrounding particles has a lot of potential: it can give explanation to the quantum entanglement phenomenon, as well as to other phenomena of the microworld. New experiments, of course, are needed to substantiate this hypothesis.

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