Nonlocality in quantum physics

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The nonlocality properties of quantum objects are considered for the example of the Aharonov-Bohm and Hanbury Brown-Twiss effects and the Einstein-Podolsky-Rosen paradox.

In modern field theory, there is a locality principle which presupposes "a mechanism of interaction between fields in which the influence of one of the fields, for example, u on the other, for example, v, has a local structure in space-time, i.e., the behavior of the field v at the point x of space-time is determined by the value of the field u (and, possibly, its derivatives) at the same point of space-time"[68] In this sense, one means by nonlocal theories an entire class of generalizations of quantum field theory based on the assumption of a nonpoint interaction.[62]

The expression nonlocality is also used in the modern literature in a somewhat different sense. There are in fact several quantum phenomena that from the classical point of view can be interpreted as the manifestation of a kind of nonlocality inherent in quantum objects. We have in mind the Aharonov-Bohm effect, the Einstein-Podolsky-Rosen paradox, the Hanbury Brown-Twiss effect, and other phenomena of this kind. The present paper is devoted to a discussion of them.

Quantum theory was unusual in that the mathematical formalism of the theory was first developed, and it was only then that the physical meaning of the formalism began to be clarified. Initially, atempts were made to construct an interpretation based on classical notions, but it very soon became clear that the task was impossible.

Already in 1910, discussing the hypothesis of corpuscular properties of light, Lorentz concluded that it is impossible to give a noncontradictory explanation of the corpuscular-wave dualism of light. He argued somewhat along the following lines[1]:

If it is assumed that a beam of light ray is a stream of particles, how is it then possible to explain interference, diffraction, and the like? Only coherent rays give a stable interference pattern, and therefore when, for example, a beam passes through a semitransparent mirror it is necessary to assume that either one photon is divided into two, and there two halves interfere with each other, or that different photons, which are coherent, interfere. But the first assumption was difficult to accept, since cases were known of interference despite a large (of the order of a meter) path difference. From this it would follow that the photons must have dimensions of the same order, which appeared unreasonable. But the other assumption, according to which the photons in a light beam form a coherent ensemble, leads to a difficulty, since it immediately poses the question of why some photons are reflected and others refracted, or why two photons arriving at a part of the screen where dark fringes are observed annihilate each other.

After the discovery of the corpuscular-wave dualism of particles (electrons), such questions became even more acute. Some physicists (de Broglie, Schrödinger, and others) attempted to develop a model that in some way combines corpuscular and wave properties of particles, but these attempts were not crowned with success.

A fundamentally new approach was proposed in the framework of the so-called Copenhagen school (Bohr, Heisenberg, Born, and others): To give a logically consistent interpretation of quantum mechanics, it is necessary to reexamine the very foundations of classical physics. Although within the Copenhagen interpretation there were many nuances in the treatment of the role of the observer and the statistical nature of the microscopic processes, these differences were largely methodological in nature.

According to this approach, until a particle interacts with some classical object it does not have definite space-time characteristics, being, as it were, simultaneously in all the regions of space in which the wave function corresponding to it is nonvanishing. In this spirit one can, for example, interpret the phenomenon of particle interference in a two-slit experiment, namely, until the particle strikes the fluorescent screen it is not localized and can be regarded as passing simultaneously through both slits used to observe the interference.

1. AHARONOV-BOHM EFFECT. MODERN INTERFERENCE EXPERIMENTS

The nonlocal properties of particles in quantum mechanics became the subject of a special discussion in the sixties in connection with the work of Aharonov and Bohm, who drew attention to the existence of a phenomenon that has become known as the Aharonov-Bohm effect.

This effect is as follows. It is known from classical electrodynamics that the behavior of a charged particle depends on the electromagnetic field only at the point of space at which the particle is situated at the given time. If in the entire region of possible motion of the particle there is no field, the motion of the particle is undisturbed. In other words, from the motion of a particle in a region free of a field it is impossible to conclude whether there is a field in other regions of space. Nevertheless, the behavior of a quantum object can be influenced by the existence of a field where the probability of finding a particle is zero. This was first pointed out by Ehrenberg and Siday[2] in a paper published in 1949. Ten years later, Aharonov and Bohm in a series of papers[3] considered this question in detail. One of the thought experiments due to Aharonov and Bohm is as follows. A plane electron wave of wavelength λ is diffracted by a screen with two slits. Behind the slits are two long conducting cylinders of length

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$l \gg \lambda$. Each of the parts of the separated wave packet passes through the corresponding cylindrical tube and, deflected by a prism, has the possibility of interfering with the other. When the packets enter the tubes, a constant potential difference is applied to them; before the packets begin to leave the tubes, the potential difference is lifted. The calculation shows that the form of the diffraction pattern depends on the potential difference applied to the cylinders, since the packets, which are affected by the potentials φ_1 and φ_2, acquire an additional phase differene proportional to $\varphi_1 - \varphi_2$. But within a cylinder the field vanishes, since the potential is constant along its length. A field exists only in the space outside the cylinders, where the probability of finding an electron is vanishingly small. Thus, from the form of the interference pattern one can deduce the existence of a field in regions of space in which from the classical point of view the charged particle is "certainly absent." Or, in other words, "the field acts where it is not." This contradicts the principle of local interaction and from the point of view of classical physics must be interpreted as action at a distance.

A similar experiment was proposed for the motion of an electron in a region an infinitely long solenoid. As in the experiment with an electric field, the plane electron wave is divided into two branches by means of a screen or deflecting prisms and passes on either side of the solenoid, which is perpendicular to the plane of the motion. The parts of the wave packet are then brought together for interference. Outside the solenoid, the magnetic field is zero. However, the vector potential outside the solenoid is nonzero, and although the electron is not affected by a magnetic field the existence of the vector potential has the consequence that the two parts of the wave packet acquire a phase difference, which determines the nature of the interference pattern.

Furry and Ramsey[6] investigated in detail both experimental situations. They showed that by introducing additional capacitors joined to the ones where the electron wave passes (in the case of an electrostatic field), or by placing a conducting circuit in the space around the solenoid, one can determine which of the paths a given electron took. But then the original interference pattern is distorted in the same way as happens in the case of diffraction of an electron by two slits if we wish to known through which slit a given particle passed.1)

In classical electrodynamics, the fields E and H are regarded as the basic physical reality, whereas the scalar and vector potentials have the significance of auxiliary mathematical concepts used to calculate the fields. The Aharonov-Bohm effect would seem to indicate that in quantum physics the potentials play a role analogous to that of fields in classical physics. This conclusion seems all the more surprising in that the potentials themselves are determined up to a gauge transformation. The "significance of electromagnetic potentials in quantum theory" (the title of one of the first papers of Aharonov and Bohm) was the subject of a particularly lively discussion. In their first paper, Aharonov and Bohm pointed out two possibilities for interpreting the effect: Either one must give up the locality principle or recognize that potentials have a physical reality no less fundamental than fields. But the second alternative would mean that it is possible to find a physical difference between states differing only in the gauge. In their following papers, Aharonov and Bohm abandoned the second alternative and interpreted the effect as a manifestation of nonlocality in the behavior of quantum objects. However, irrespective of the interpretation, the Aharonov-Bohm effect could be regarded from the classical point of view as a proof of action at a distance. But the quantum nature of the phenomenon does not permit us to draw such a conclusion. The dichotomy between action at a distance and local interaction, formulated in the language of classical concepts of localized particles, ceases to be valid in the domain of quantum physics, in which the notion of a localized object can be introduced only artificially.2) As Furry and Ramsey showed,[6] the Aharonov-Bohm effect is observed only under experimental conditions for which one certainly cannot speak of a localized particle, and the phenomenon completely disappears if one measures the coordinate, i.e., localizes the particles, in any way.

A further illustration of the nonlocality of quantum objects is provided by the interference experiments made in the sixties by Pfleegor, Mandel, and Magyar.[9] They showed that overlapping beams of two lasers can give an interference pattern. At first glance, these results contradict Dirac's conception of a photon, according to which "each photon interferes only with itself. Interference between two photons never occurs."[10] "Arguing classically," one might think that since the two photon beams arise in two different lasers, the observed effect is due to the interaction between two different photons. But the experiments do not permit such a conclusion, since the interference pattern remains even when the light beam incident on the detector is reduced so much that not more than one photon can be in the space between the attenuating filter and the detector.

From the classial point of view, this result appears unexpected; for although the "photon interferes only with itself,"[10] both lasers play an equally important part in forming the interference pattern, which changes when one of them is switched off. How can a photon emitted by one laser "know" whether the other is switched on or off?

In fact, this situation is no more paradoxical than Young's interference experiments with two slits, in which too the photon "interacts with itself" and "knows" the state of two slits simultaneously.

The root of the paradox is to be sought in the classical picture of a localized particle, or photon. To ask after the laser that emits a given photon has from the quantum-mechanial point of view no more meaning than to ask after the

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1)The first experimental confirmations of the existence of the effect were obtained already at the beginning of the sixties.[4] However, the interpretation of these experiments is still the subject of discussion, stimulated in large degree by the series of papers published by Bocchieri and Loingier.[5] These authors assume that the Aharonov-Bohm effect has a purely mathematical origin and cannot in reality be observed, and that the existing effects are to be explained by ignored artifacts. Numerous authors[3] have criticized the arguments of Bocchieri and Loingier, pointing out that the Ahronov-Bohm effect has been convincingly proved both theoretically and experimentally. Among the most recent experiments we mentioned Ref. 71, which is of interest in particular in that toroidal magnets were used in order to eliminate edge effects.

2)For more details, see Ref. 8.

slit through which the photon passes in Young's experiment. In either case the attempt to "follow" the flight of the photon through the slits or to "label" the photons emitted by the lasers necessarily destroys the original interference pattern.

Thus, the "intuitively clear" classical picture of independent atoms, each emitting its "own" photon, is invalid in the present case. A quantum system radiates as a single entity even when its various parts are separated by a macroscopic distance.[3)]

As Sciamanda emphasizes,[11] one should see "all photon sources in the Universe merely as one source with a certain spatial distribution, and calculate the total wave function of this "world source." Indeed, the division of the world source into independent pats is in general quite arbitrary. . . . It is only under special experimental situations that one can associate a definite source location with an observed photon, i.e., when the probability amplitude for paths from all other sources to the observation is negligibly small."

This property of "nondecomposability" inherent in quantum sources can also be demonstrated by the Hanbury Brown-Twiss effect,[12] the "interference of intensities." The effect is as follows. Suppose we have two light sources A and B at a large distance from two photon detectors a and b. The detectors are connected to a coincidence circuit that detects the number of photons that arrive simultaneously at a and b. Then, as a calculation shows,[13] the number of coincidences is a periodic function of $R_2 - R_1$, where R_1 is the distance betwen A and a, and R_2 is the distance between B and b. The quantum feature of the calculation is the impossibility of distinguishing photons which arrive at a from A from photons that arrive at a from B. If the experiment is arranged in such a way that such a distinction becomes possible, the effect disappears.

Of course, the effect appears paradoxical from the point of view of classical notions, since it means that photons emitted by two "independent" sources "know" the behavior of each other. But, as we see, this "independence" is itself a classical abstraction that is meaningful only under conditions of an experiment in which some "labeling" makes it possible to distinguish the photons that arrive from different sources. But then the effect disappears, and intensities, and not amplitudes, are added.

2. THE EINSTEIN-PODOLSKY-ROSEN PARADOX

One of the most interesting aspects of nonlocality in quantum mechanics was revealed by the Einstein-Podolsky-Rosen (EPR) paradox.

This paradox was first formulated in a paper by these authors in 1935 with the title "Can quantum-mechanical description of physical reality be considered complete?"

Einstein and his collaborators begin by explaining what they understand by a complete theory and by physical reality. "Whatever the meaning assigned to the term *complete*, the following requirement for a complete theory seems to be a necessary one: *every element of the physical reality must have a counterpart in the physical theory.*"[58a] The meaning of this definition depends on the content of the expression *element of physical reality*. What is the condition under which one can assume that something (an object or a quality of this object) has physical reality? The following definition is provided: "If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."[58a] The authors illustrate this definition by pointing out that if a physical system is in a state described by the eigenfunction of some operator A, i.e., if $A\psi = a\psi$, then the physical quantity corresponding to this operator has the value a. Further, they emphasize that according to quantum mechanics a system cannot be simultaneously in eigenstates of two noncommuting operators. Therefore, for noncommuting operators the physical quantities corresponding to them cannot exist simultaneously.

The authors advance the following dilemma: "Either (1) the quantum-mechanical description of reality given by the wave function is not complete or (2) when the operators corresponding to two physical quantities do not commute the two quantities cannot have simultaneous reality."[58a]

Einstein, Podolsky, and Rosen show that if one adopts their criterion of reality, the wave function does not give a complete description of a physical system. Two systems I and II that interact for a certain time are considered; they could, for example, be two particles which then separate. According to quantum mechanics, their state is described by a common wave function. Einstein, Rosen, and Podolsky show that as a result of two different measurements made on the first system the second system may be in two different states described by different wave functions. According to them, the situation is paradoxical: "Since at the time of measurement the two systems no longer interact, no real change can take place in the second system in consequence of anything that may be done to the first system . . . . Thus, *it is possible to assign two different wave functions . . . to the same reality* (the second system after the interaction with the first)."[58a] This is all the more paradoxical in that the corresponding wave functions may be eigenfunctions of two noncommuting operators P and Q. In such a case, making a measurement on the first system, one can predict with certainty and without any disturbance of the second system the values of the corresponding quantities for this system. But since the measurement of the first system in no way affects the second, it is necessary to recognize that for the second system the physical quantities corresponding to P and Q exist simultaneously. "We are thus forced to conclude that the quantum-mechanical description of physical reality given by wave mechanics is not complete."[58a]

At the end of the paper, the authors make two important comments. The first of them defends their definition of physical reality from criticism. "One could object to this

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[3)] As one further illustration of this, one can consider a Michelson interferometer. Since the observed pattern depends on the mutual position of the mirrors, a photon interacts in a certain sense with both of them. However, this interaction cannot be interpreted classically as absorption and emission of parts of the photon by an individual mirror: A quantum can be absorbed only as a whole. Therefore, the two mirrors together are to be regarded as a secondary emitter, analogous to the two-laser arrangement of Pfleegor and Mandel.

conclusion on the grounds that our criterion of reality is not sufficiently restrictive. Indeed, one would not arrive at our conclusion if one insisted that two or more physical quantities can be regarded as simultaneous elements of reality *only when they can be simultaneously measured or predicted*. On this point of view, since either one or the other, but not both simultaneously, of the quantities P and Q can be predicted, they are not simultaneously real."[58a] But Einstein, Rosen, and Podolsky reject this objection in advance, since then the reality of these quantities for the second system depends on the measurement made on the first. But this is impossible since "no reasonable definition of reality could be expected to permit this."[58a]

Bohr's answer followed less than two months after the appearance of the EPR paper. His arguments were aimed against Einstein's concept of reality: "A criterion of reality like that proposed by the named authors contains," writes Bohr, "an essential ambiguity when it is applied to the actual problems with which we are here concerned."[15a] The origin of the ambiguity was explained by Bohr both in his 1935 paper as well as many others devoted to methodological problems of the quantum theory.

Einstein's main error, in Bohr's opinion, is that he ascribes to quantum objects the existence of properties independently of the real experimental situation in which these properties are manifested. Such an approach, justified in classical physics, is impossible in the quantum case[15)]: "We encounter in atomic physics an entirely new situation in which it is in principle impossible to make a clear distinction between the internal properties of objects and their interaction with the measuring instruments that must be used for the very observation of these properties" (Ref. 15b, p. 383). Thus, Bohr assumes that the EPR paradox, which derives from the apparent incompatibility of the properties of an object observed under different experimental conditions, finds its explanation in the fact that the experimental arrangements needed to make these observations are mutually exclusive. In other words, the fact that by measuring the momentum of one particle we can with certainty predict the result of measurement of the momentum of the other does not at all mean, in Bohr's view, that the momentum of the second particle really exists before its actual measurement.

After the publication of these papers by Einstein and his collaborators and Bohr, the paradox was frequently analyzed. Many differnt opinions were expressed about the views of both Einstein and Bohr; see, for example, Refs. 16–18. The most widespread opinion was the one based on the Copenhagen interpretation of quantum mechanics. This reduces to saying that before the measurement neither particle is localized in space, so that there is no meaning in saying that they have become separated by a large distance. They are to be regarded as simultaneously everywhere, since their wave function is distributed over the whole of space. To be certain that they are separated by a large distance, it is necessary to make a measurement on them, and this destroys their common wave function. Here, measurement does not necessarily mean direct interaction of an instrument with an object. It is possible to make an indirect measurement, which does not in any way differ fundamentally from a direct one.

However, this approach to the solution of the EPR paradox did not satisfy everyone, and other ideas were put forward. It was suggested that the paradox can be eliminated if it is assumed that the wave function describes, not one particle, but a statistical ensemble of the system. Then the measurement, for example, of the momentum of one particle will be equivalent to choosing a corresponding subensemble as part of the complete ensemble described by the function ψ. In this case, the correlation between the two particles has a statistical nature, and this eliminates the entire paradox.

Einstein himself recognized the possibility of such a formulation of the problem, but felt that in this case quantum mechanics cannot be regarded as a complete theory, since it does not give a description of the behavior of individual microscopic objects. He wrote: "Ultimately, we cannot avoid the view that physics must strive for a real descripton of an individual system. For nature as a whole can only be thought of as an individual (existing once) system and not as an "ensemble of systems."[58b]

A different solution of the EPR paradox was proposed by V. A. Fock and A. D. Aleksandrov, who put forward the idea of a "nonforce interaction" of quantum objects. In his commentary on Einstein's "Autobiographical notes," Fock wrote that Einstein's mistake was in denying all interactions apart from force interactions. In Fock's opinion, a feature of the behavior of quantum objects revealed by the EPR paradox is a clear indication of the existence of a "nonforce interaction." In his view, another example of such interaction is the correlation in the behavior of microscopic objects expressed by the Pauli principle.[19]

Aleksandrov[20] also assumes that there is an error in the arguments of Einsten, Podolsky, and Rosen. It consists of assuming that separated particles no longer interact. Such an assumption is in complete agreement with classical ideas but is not correct form the quantum point of view. It is precisely the fact that quantum mechanics ascribes a ψ function only to the two particles together and not to each separately that is, in Aleksandrov's opinion, an indication of the existence of a special nonforce connection between them. "We cannot picture to ourselves this connection clearly, it may be unusual..., but we must recognize the presence of connections if we take quantum mechanics seriously and assume that the ψ function represents the state," emphasizes Aleksandrov.[20]

As another example of a nonforce interaction, he considers interference from two mirrors. The interference pattern, which is determined by the position of the mirrors, means that an individual photon feels an "effect of the mirrors" that is not associated with transfer of energy and momentum.

Similar positions are adopted by Lomsadze and Lomsadze.[61] They assume that a measurement on one of two correlated particles changes the state of the other, this material interaction being propagated arbitrarily fast. They emphasize however that this process cannot serve as a basis for communicating information.

We also mention Bohm's point of view with regard to the EPR paradox. In connection with his interpretation of quantum mechanics proposed in the fifties on the basis of the idea of hidden variables, Bohm considered the EPR paradox. In his theory, Bohm assumed that besides the oridnary force interaction there is between quantum objects another form of interaction with forces that propagate instantaneously, their magnitude being either quite independent of the distance or dependent on it in some unusual manner. If one accepts the existence of such forces, it can be assumed that interaction between separated particles does not stop even at large distances.[54] There are also other approaches to the resolution of the paradox, on which we shall not dwell.

In his book Quantum Theory, Bohm considered a new variant of an EPR though experiment.[22] A molecule in the singlect state breaks up into two atoms, each of which has spin $\frac{1}{2}$. After the decay, the total angular momentum of the two particles must still be zero by virtue of angular momentum conservation.

If we now measure the projection onto the X axis of the angular momentum of the first body, we obtain, for example, the value σ_x. After this we can assert that the spin component of the second particle along the X axis is $-\sigma_x$. But since before the measurement we did not influence the second particle, it follows from Einstein's argument that the projection of the angular momentum along the X axis for the second particle is $-\sigma_x$ before its measurement. But we can measure the projection of the angular momentum of the first particle onto the Y axis, obtaining the value σ_y, and then the other particle will have the component $-\sigma_y$ along this axis. But quantum mechanics does not permit one particle to have definite values of two components of the angular momentum simultaneously. Thus, we arrive at the same paradox as Einstein, Podolsky, and Rosen. Although the variant of the EPR paradox considered by Bohm does not differ in principle from the original paradox, it is simpler for theoretical analysis. Moreover, one could hope that the experiment proposed by Bohm could be not only a thought experiment but one actually performed.

A further modification of the EPR experiment was proposed by Aharonov and Bohm[23] in 1957. The experiment was now concerned with photons. The annihilation of an electron and a positron gives rise to two photons (two γ rays). A calculation shows that the emitted photons are always in a state with polarizations in mutually perpendicular directions.

Measuring now the polarization for one photon, we simultaneously know the polarization of the other without directly measuring it. But it must be emphasized that the emitted photons do not have a definite polarization. Thus, in this case the aspect of quantum mechanics expressed by the EPR paradox is manifested in the simplest form.

3. BELL'S THEOREM

Since the sixties, the EPR paradox has been discussed in connection with Bell's theorem on the possibility of introducing in quantum mechanics so-called hidden variables. Many eminent physicists (Einstein, Schrödinger, de Broglie, Bohm, and others) have considered the possibility of creating a deterministic theory of microscopic phenomena that includes quantum mechanics. However, it was more widely believed that hidden variables cannot be introduced into a theory of microscopic phenomena.

An important part in establishing this view was played by the work of von Neumann,[55] who proposed a proof of the incompatibility of a theory of hidden variables with the basic propositions of quantum mechanics. Von Neumann's work stimulated a discussion, in the course of which it became clear that his proof cannot be regarded as final, since it is based on assumptions that, in general, are not necessary for all models of hidden variables. A more general proof of von Neumann's thesis was given by Jauch and Piron,[56] and then Kohen and Specker.[57]

In 1965, Bell published a paper[14] in which the problem of hidden variables was considered from a new and, as subsequently became clear, very fruitful point of view. He proved a theorem which is as follows: Theories of hidden variables that reproduce all the results of quantum mechanics must be essentially nonlocal. By locality, Bell understands the following requirement: A measurement made at a point A must not influence the results of a measurement made at a point B.

Bell considered a thought experiment analogous to the EPR case. Suppose that the results of correlation measurements are ultimately determined by the values taken by hidden variables which "control" the behavior of particles, no assumptions being made about the properties of the hidden variables except that they must satisfy the locality principle. Then, as Bell showed, the results of such an experiment must satisfy a simple inequality, which is known as Bell's inequality. Its physical meaning can be readily understood by considering the following concrete example.

Consider pairs of diatomic atoms produced by the decay of a diatomic molecule in the singlet state. These atoms are emitted in opposite directions, and in accordance with the conservation of angular momentum the projections of the spins of such atoms onto an axis have opposite values. These projections can be measured by means of two identical Stern-Gerlach devices, placed in the paths of the atoms. The axes of the devices (i.e., the direction of the magnetic field) can be oriented along any vector in the plane perpendicular to the line along which the atoms are emitted.[4] Consider three such vectors: A, B, C. Suppose that the axis of the left-hand analyzer is parallel to A and of that at the right to B. We now denote by $n(A, B)$ the probability that the atom passing the left-hand polarizer is "up" along the A axis, while its "twin" traverses the magnetic field of the right-hand analyzer "down" along the B axis. We define $n(A, C)$ and $n(B, C)$ similarly. Then, as Bell showed, the numbers $n(A, B)$ $n(B, C)$, and $n(A, C)$ must satisfy the inequality

$$|n(A,B) - n(A,C)| + n(C,B) + n(C,C) \leqslant 2.$$

But the quantum mechanical calculation shows that for certain orientations of the axes this inequality must be vio-

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[4] In the context of the given experiment, the locality condition means that the relative number of particles detected in the channels of one detector does not depend on the orientation of the axis of the other.

lated. Thus, the predictions of quantum mechanics must contradict the notion of local hidden variables. Hence, if hidden variables do exist they must be essentially nonlocal, a measurement made on one particle influencing the values of the hidden variables that control the motion of the other.

Bell's work is interesting in that it identifies an entire class of physical situations in which the predictions of quantum mechanics and theories of hidden variables can differ. However, from the purely experimental point of view uncertainty remained, since at the time Bell found his inequality no experiment had been made that could test it. Moreover, the very possibility of a test using the existing technology was far from obvious. The point was that Bell derived his inequality by considering a strongly idealized experiment that did not correspond to the actual properties of detectors.

The situation changed in 1969, when Clauser, Horne, Shimony, and Holt[24] published a paper which demonstrated the basic technological possibility of the experiment. Making very reasonable assumptions about the properties of the detecting apparatus, they derived an inequlity (known as the Bell-Clauser-Horne-Shimony-Holt inequality), which served as an experimentally verifiable form of Bell's inequality. They also advanced an idea for measuring the correlation of the polarizations of photons emitted by an atomic cascade transition; this experiment was later realized by Freedman and Clauser in 1972.[25]

Bell's work stimulated discussion on the problems it raised. This disccussion is still far from complete, but we can already say something about its most "invariant component"—the results of the experiments made with the direct aim of testing Bell's inequality.

Before we turn to a description of the actual experiments, we point out, that irrespective of the form of the investigated particles, each such experiment consists of four series of correlation measurements. One fixes three directions A, B, C in the plane perpendicular to the direction of emission of the particles, the angles between them being chosen such that the difference between the predictions on the levels of the correlations that follow from quantum mechanics and a theory of local hidden variables is maximal. In the first series of measurements, one filter (for example, the polarizer) and the detector placed behind it detect particles having plane of the polarization parallel to the A axis. The second filter, which has orientation parallel to B, and the detector make a similar measurement with the particles emitted in the opposite direction. A coincidence circuit measures the level of correlation between the counts of the detectors. After a statistically reliable series of measurements has been made, the position of one of the filters (for example, the second) is changed; it is turned to the position C, and the correlation level is measured for the axes A and C. In the third series of measurements, the filters take the positions B and C. To obtain a normalizing estimate for the efficiency of operation of the filters, detectors, and coincidence circuits, one measures the coincidence levels under conditions when one of the filters or both at once are absent. The results obtained in the four series of measurements are compared in the context of the Bell-Clauser-Horne-Shimony-Holt inequality, violation of this inequality serving as experimental evidence for violation of Bell's inequality.

The experiments so far made can be divided into three groups on the basis of the species of correlated particles.

The experiments of the first type measured the correlations between the polarizations of photons emitted by cascade de-excitation of excited atoms. The first such experiment was made by Freedman and Clauser[25] in 1972. Their results revealed a violation of Bell's inequality and, therefore, confirmed the prediction of quantum mechanics. Similar experiments were made in 1976 by Fry and Thompson[26] and Clauser,[27] and in 1981–1982 by Aspect, Grangier, and Roger[69]; their conclusions confirm those of Freedman and Clauser.

In contradiction with these was the experiment of Holt and Pipkin, made in 1973.[28] Their results do not violate Bell's inequality and, thus, disagree with both the predictions of quantum mechanics and the results of the Freedman-Clauser and Fry-Thompson experiments.

The experiments of the second type measured the correlations between the polarizations of γ rays emitted by positron-electron annihilation. Historically, these experiments were preceded by the experiment in 1949 of Wu and Shaknov,[29] which for the first time confirmed quantum theory's predictions of the existence of such correlations, although the results of the experiment could not serve as a test of Bell's inequality.

In 1974, Faraci *et al.*[30] published unexpected experimental results, namely, the measured data did not violate Bell's inequality and, thus, contradicted quantum mechanics. In 1975, results of experiments made at the University of Columbia were published. Making a similar experiment, Kasday, Ullman, and Wu[31] obtained a result that violated Bell's inequality and, therefore, confirmed the prediction of quantum mechanics.

In 1977, Bruno, d'Agostino, and Maroni made a similar experiment at the University of Bologna and obtained a result in agreement with that of Kasday, Ullman, and Wu.[32]

In the experiments of the third type, pairs of protons are investigated after collision. Such an experiment was made in 1975 by Lamehi-Rachti and Mittig.[33] A proton beam from an accelerator is directed onto a target that contains hydrogen atoms. The proton pairs produced as a result are emitted in the singlet state, and the projections of their spins onto given axes are correlated. The results of the measurements revealed violation of Bell's inequality. It should be noted that so far this is the only experiment in which measurements were made on particles with nonvanishing rest mass; in all the other experiments the particles were photons.

Thus, most of the experiments so far made[5)] have confirmed the predictions of quantum mechanics, Bell's inequality being not violated in only two. It can therefore be assumed with some confidence that quantum mechanics has been confirmed—for this time—in a series of EPR correlation experiments. But how is one to evaluate the "anomalous" results of the Holt-Pipkin and Faraci experiments?

[5)] The present paper was written in spring 1983.

This question is still somewhat obscure,[6)] but the most probable explanation is as follows. As follows from Bell's arguments, quantum mechanics predicts a greater degree of correlation between phenomena than any theory of local hidden variables. However, imperfections of the detectors and the coincidence circuits can have the consequence that the observed correlation level is significantly lower than the real level. The lower the level of the correlations, the greater is the possibility that the results of the measurements will not violate Bell's inequality. In this sense, to refute the theory of local hidden variables it is sufficient if there is one experiment in which Bell's inequality is violated (just as to refute the law of conservation of energy it would be sufficient to construct just one working example of a perpetual motion machine).

Thus, there are very good grounds for believing that the correlation experiments made to test Bell's inequality have confirmed quantum mechanics. Therefore, the problem that arose with Bell's work appears to be largely dealt with: If hidden variables do exist, they must be essentially nonlocal.

4. LOCALITY AND SEPARABILITY

A new and very interesting approach to the problem was formulated by Aspect in Ref. 34. He suggested that one should distinguish the concepts of locality and separability (used hitherto as synonyms). His distinction is as follows. According to Bell, nonlocality means that measurement of one particle can influence the behavior of the other. But how rapidly is such an influence manifested?[7)] If it arises within a time less than is necessary for light to pass from one detector to the other, during the time between the measurements at A and B, then in this case the measurements are not only nonlocal but also nonseparable.

The "principle of separability" formulated by Aspect is as follows: The nature of a measurement made by the instrument A at a definite time (event A) must not influence the result obtained by a different measurement by the detector B (event B) if event B does not lie in the timelike part of the light cone with apex at A.[8)] The experiments hitherto made do not attack the separability problem. To solve it, one must make an experiment in which the orientation of the axes of the analyzers is changed sufficiently rapidly, i.e., during an interval of time certainly less than the time required for a light ray to pass from one detector to the other.

Such an experiment was made in 1982 by Aspect, Dalibard, and Roger.[70] It showed that Bell's inequality is also violated under the conditions of an experiment with rapidly changed axes of the analyzers. Thus, it follows from the experiment that if there are hidden parameters they must be both nonlocal and nonseparable.

a) Locality or determinism?

At the end of the seventies, the validity of Bell's theorem and the reliability of the experimental results became widely accepted. The discussion now concentrates on the conclusions that follow from Bell's theorem. As we have seen, this theorem makes it necessary to choose between determinism and locality. Depending on the solution of this question one can identify (though to some extent arbitrarily) two tendencies in the approach to the problem of locality.

The first (and numerically larger) group of authors assume that the observed violation of Bell's inequality cannot be taken as unambiguous evidence for the breakdown of locality. It is assumed that the probabilistic nature of quantum mechanics is fundamental, i.e., is not due to any deterministic hidden variables. From this point of view,[9)] staying to a large degree within the framework of the Copenhagen approach, all pairs of correlated particles are identical and there is no particular meaning in saying that the result of an interaction is in some way determined before it actually arises in the process of the experiment. Therefore, the very concept of locality has a meaning different from that in the case when the validity of determinism is accepted. Since identical initial conditions need not necessarily lead to identical final states, it becomes impossible to give a clear meaning to the actual definitions of locality: The result of the interaction of particle a with the instrument A does not depend on the state of the instrument B. All that a change in the state of instrument B can influence are the probabilities of the different results of a mass correlation experiment. Therefore, it is more precise to express the situation by the term "statistical locality," which is all that can be given a clear experimental meaning. From this point of view, if there is a violation of locality, it does not have a statistical nature and is, in the best case, a property of each pair of particles. Therefore, the assumption that there exists some "hidden determinism" necessarily leads to a problem, namely, how can one explain the violation of locality for individual phenomena while "statistical locality" remains valid.

A basically different point of view is adopted by the other group of authors, for whom nature is fundamentally deterministic and the experiments to test Bell's inequality clearly indicate a breakdown of locality.[36–47,64,66] Such a position immediately poses at least two questions. The first is: What is the real physical process by virtue of which a measurement made on particle b by the device B can influence the interaction of the particle with instrument A? In principle, one can assume the existence of some field that emanates from B and influences the operation of instrument A or the behavior of particle a. However, it is strange that the influence must be independent of the distance between A and B.[10)] The second question is: With what velocity does the interaction propagate? It follows from the experiment of Aspect, Dalibard, and Roger that it is greater than the velocity of light, but some authors still insist that some physical process carrying information from one instrument to the other is responsible for the violation of locality.

[6)] Of course, it could be assumed that they are simply wrong.

[7)] If, of course, it exists at all.

[8)] It is clear from the definition of separability given here that it is essentially an assertion of the impossibility of the propagation of physical processes with velocity greater than the velocity of light formulated in the context of a correlation experiment.

[9)] Presented very clearly, for example, in Ref. 35.

[10)] The level of correlations between the counts of the detectors at A and B does not depend on the distance between them. This follows from the meaning of the conservation law and has been confirmed recently in an experiment by Wilson, Lowe, and Butt,[50] made specially in order to establish this independence.

This point of view has been developed most systematically and specifically by Cufaro Petroni and Vigier.[46,47] They construct a "causal theory of microscopic phenomena in the framework of a model of a fluid with irregular stochastic fluctuations," as proposed in 1958 by Bohm and Vigier.[49] This theory is one of the variants of the theory of hidden variables.

Some authors[36–38] developed the idea that the violation of locality must be interpreted in the framework of the Wheeler-Feynman theory of action at a distance, in which retarded and advanced physical interactions are treated on an equal footing. In this scheme, the correlations between the readings of the instruments are explained by the fact that through advanced waves ("telegraph to the future") information from device B propagates to the source of the photons and in some way influences their polarization. In such an approach, relativistic invariance is maintained, but one necessarily reproduces the difficulties characteristic of a theory of action at a distance, in particular, the breakdown in the time ordering between cause and effect.[21]

b) Is "superluminal telegraph" possible?

As we have seen, the situation described by the EPR thought experiment can be regarded as paradoxical or not depending on the general views about nature and scientific knowledge adopted by the various scientists. The interpretation of the violation of Bell's inequality in the correlation experiments can differ in accordance with these different views. There is however a question whose answer can advance these differences from being purely "methodological" and thus make it possible to compare the heuristic value of the different interpretations. The question is whether the reduction of the wave function (which occurs, for example, in a correlation experiment when the parameters of one of the particles is measured) corresponds to a physical process that propagates with superluminal velocity. From the "orthodox" point of view, this question has a negative answer. It is said that in a measurement made on one particle all that changes is our knowledge about the results of a future measurement of the parameters of the other particle, but not its actual state.

Many authors who interpret the violation of Bell's inequality as evidence for nonlocality also assume that superluminal processes exist. However, their arguments differ in the degree to which they are concrete.

In a paper entitled "Are superluminal connections necessary?" Stapp writes: "The central mystery of quantum theory is 'How does information get around so quick?' How does the particle know that there are two slits? How does the information about what is happening everywhere else get collected to determine what is likely to happen here? . . . . Quantum phenomena provide *pima facie* evidence that information gets around in ways that do not confirm to classical ideas. Thus the idea that information is transferred superluminally is, *a priori*, not unreasonable."[51] However, this does not mean that such processes can be observed directly: "everything we know about nature is in accord with the idea that the *fundamental* [our italics; B. S., A. M.] processes of Nature lie outside space-time . . . , but generate events that can be located in space-time."[51]

From the above quotation we see that Stapp's arguments in support of the existence of superluminal velocities is of an "intuitive" nature and can not be regarded as a direct proof. It also remains not clear as to what meaning should be ascribed to the concept of the rate of occurrence of processes lying "outside the bounds of space-time."

More concrete arguments are advanced by Cufaro Petroni and Vigier.[47] They consider a correlation experiment in which the state of one of the analyzers (for example, B) is changed rapidly by the experimentalist situated at B. Initially, the axes of the instruments are oriented so that there is the maximal correlation in their readings. Then, at a certain instant the position of the instrument B is rapidly changed to a position in which the correlation completely disappears. The task of the observer at A is to identify this instant. Of course, the observer at A, who knows only the readings of his instrument, cannot do this, but, on being acquainted with the protocol of observer B and comparing it with his, he establishes the time at which the instrument at B was rotated. Of course, he must obtain such a protocol by means of an "ordinary" signal sent from B.

Thus, the process of obtaining information from B at A consists of two stages—the receiving of a "coded" signal in the form of the protocol of the observations at A and then "decoding" it by means of the "key" in the form of the protocol of the observer at B.

However, this argument, which is not lacking in ingenuity, still does not have the last and fundamentally important link—the proof that the amount of information decoded by observer A exceeds the amount of information obtained by him in the form of the protocol of the observer B. It is easy to see that this is not so,[11)] and therefore the argument of Cufaro Petroni and Vigier does not achieve its aim.

Another argument for the existence of a superluminal connection is given by Herbert in Refs. 45 and 72. He assumes that the experimental scheme that he proposes can serve as the physical basis for the creation of a real "superluminal telegraph."

A source that is the same for optical instruments at A and B emits correlated pairs of photons in the optical range; the source is slightly closer to B, so that the interval between the photon absorption events is spacelike. The apparatus B, which is the source of the information transmittted to A, consists of a pair of additional analyzers—a device for measuring the plane of the polarization and a device that determines the direction of rotation of the plane of polarization. The device at A consists solely of a half-wave plate with ap-

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[11)] Indeed, establishing by comparison of the protocols which of the two possible positions the B axis occupies, the A observer "decodes" 1 bit of information. However, to draw this conclusion with at least minimal degree of confidence, he must have the protocols of the measurements for one pair of particles, extracting 1 bit of information from the B protocol. Since random coincidences of the responses can occur for any mutual orientation of the axes, to increase the reliability of his conclusions the A observer must use the largest possible number of pair responses for the analysis. But then the ratio of the amount of "decoded" information to the amount used becomes even less; see also Refs. 59, 63, and 65.

propriate orientation. Such a plate reverses the direction of rotation of a circularly polarized light beam and does not affect a plane-polarized beam if its plane of polarization coincides with one of the planes of the plate. A circularly polarized photon passing through the plate changes its momentum; there is no reaction of the plate in the case of a plane-polarized beam. According to Herbert, the particles that arrive at A will have different kinds of polarization depending on the type of device used at B to detect the passing photons, and, measuring the "recoil" of the plate at A, one can draw a conclusion about the type of instrument at B. This is the superluminal telegraph!

It should be noted that Herbert's arguments are based on two assumptions that are very "unorthodox" from the point of view of quantum mechanics, namely, that individual photons have a definite kind of polarization before interaction with the analyzer,[12)] and that the way photon a is polarized depends on the interaction of photon b with its instrument.

Ghirardi and Weber[52] pointed out a further error in Herbert's arguments. A quantum-mechanical calculation shows that an ideal half-wave plate must have an infinitely large mass; but in such a case measurement of its reaction becomes impossible, and a plate of finite mass cannot unambiguously distinguish circularly and linearly polarized photons.[13)]

Thus, none of the arguments we have considered for the existence of superluminal signals is satisfactory.

5. CONCLUSIONS

We have seen that the problem of "nonlocality in quantum physics" encompases two groups of questions. In the first we can consider phenomena whose physical interpretation does not give rise to discussion. These are the Aharonov-Bohm, Hanbury Brown-Twiss, etc., effects discussed in Sec. 2. They demonstrate that aspects of a specific wholeness are inherent in quantum objects and, considered classically, can create the illusion of a certain kind of "action at a distance": A particle diffracted by two slits appears to "know" the state of both slits simultaneously; a field acts where it is absent in the Aharonov-Bohm effect, and so forth. The basis of this illusion is the classcial picture of the world of a collection of objects that are localized and are therefore relatively independent of each other. Every correlation in their behavior is explained then ultimately by an interaction, i.e., by the exchange of energy and momentum. In such a context, the concepts of local interaction and action at a distance have a clear meaning and serve as two variants of the answer to the question of whether causal connections are spatially continuous.

But a quantum object is neither a particle localized in space nor a classically understood wave but some third entity that manifests the properties of these classical models only in some limiting experimental situations. Therefore, the dilemma posed by the conflict between local interaction and action at a distance loses its clear meaning in quantum physics. The expression "nonlocality," which can be regarded as a "quantum analog" of action at a distance, corresponds better to the essence of the matter.

In prerelativistic physics, the finiteness of the velocity of light is one of the conclusions of the "scientific-research program" of local interaction concretely realized by the Maxwell-Lorentz electrodynamics. In relativistic physics, this proposition acquires the nature of a postulate. The principle of the constancy of the velocity of light, which is also valid in quantum physics, for which the concept of spatially continuous causal links loses a clear meaning, can be regarded as a "quantum analog" of the concept of local interaction. The "principle of separability" formulated by Aspect in the context of the Einstein correlation experiment is a simple consequence of it.

Another group of questions associated with the problem of locality is concentrated around Bell's theorem. In recent years, this group has been the one giving rise to the most lively discussions and interesting from the physical and methodological points of view. One of the questions actively discussed here is whether quantum correlation should be regarded as fundamental property of nature of whether it should be explained in the framework of an approach different from the existing theory. Attempts at such an explanation continue, but they are all either inadequately developed or contain too exotic assumptions and conclusions, and they have therefore not found many supporters. The traditional point of view remains the most influential: The laws of quantum physics cannot be reduced to any form of "hidden determinism."

Such an approach contains two paradoxes.[14)] One of them is well known and has been discussed frequently: The behavior of individual microscopic objects cannot be directly predicted but quantum mechanics can describe the behavior of an ensemble of such objects with any degree of accuracy. Another paradox became clear in the context of Bell's theorem. In a correlation experiment, it is possible to predict (ideally, with 100% probability) the outcome of an individual event. But this means we can predict the outcome of an event that does not have a cause!

Expressing his attitude to quantum indeterminism, Einstein once remarked that, in his view, "God does not play dice." Let us use this metaphor of Einstein to discuss the correlation experiment. Then, adopting the point of view of locality, we must say that as long as the dice are in the air they have no marks on their faces (the hidden parameters are absent). The marks—which moreover are the same ones—arise only when the dice come to a stop. When does nature make its choice? Before the dice begin to fall? It is natural to

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[12)] This assertion is analogous to the thesis that a microscopic object has a definite coordinate or momentum irrespective of the actual experimental situation.

[13)] The situation is similar to the one found by Bohr when analyzing the idealized experiments proposed by Einstein to refute the uncertainty principle; for more details, see Ref. 15, p. 399.

[14)] We emphasize that in the word "paradox" we do not place any negative meaning; a paradox (in contrast to a paralogism) is not something that needs to be eliminated, since it draws attention to some unexpected "strange" property of nature (its "secret,"—Feynman). "Copernicus's heliocentrism was once a paradox. The problem with a true paradox . . . is in expressing it, "writes O. Costa de Beauregard (Ref. 48, p. 53).

think this way from the classical point of view, but Bell's theorem plust the requirement of locality forbids our making such a conclusion. Does it happen when the first die comes to a stop? But it is then unclear how this event can influence what occurs to the second die. We must evidently assume that for nature two dice thrown from one box (or, speaking more specifically, two particles produced by a single emission or annihilation event, for example) are essentially a single indivisible object (the corrected particles have a common wave function) and their impinging on the table (the interaction of the particles with the microinstrument) is in some sense one event (or, in other words, one "bi-event"), which can be divided into two only with a certain degree of arbitrariness, just as the nucleus of an atom can be regarded as consisting of protons and neutrons only very nominally.

Consideration of the correlation experiment also makes it possible to see how the classical and quantum mechanical understandings of the conservation laws differ. In classical physics for something to be conserved means that it must exist—continuously and in unchanged amount. We speak, for example, of momentum conservation, understanding thereby some portions of matter that "have" momentum and exchange it in such a way that the total momentum continuously remains definite and unchanged. The description of microscopic objects is impossible without specifying the experimental situation in which they are investigated, and therefore it is not always possible to speak of characteristics of an object that are inherent in it continuously and irrespective of the experimental context. The conservation laws are then the most concentrated expression of the correlations in the behavior of microscopic objects under identical conditions.

Concluding this paper, we remark that the experiment of Aspect, Dalibard, and Roger completes a definite stage in the discussion about locality and hidden parameters. The discussion itself will undoubtedly continue. To justify this statement, we conclude with some words of Prigogine[67]: "The questions that Einstein has posed are still with us . . . .Einstein could not find a contradiction in quantum mechanics, and in this sense Bohr was the victor, but it is no less true that an increasing number of physicists are unsatisfied with what is called the "Copenhagen interpretation." Bohr wished, in some way, to take quantum mechanics as it was and to prove the fruitlessness of searches for a "deeper" interpretation of its formalism. From this point of view, Einstein was the victor. Today, more than 50 years later, numerous scientific journals publish papers discussing hidden variables, the problems of measurement in quantum mechanics, and the significance of irreversibility. This flood of papers, which appears unstoppable, would probably be even greater if journals with serious reputation did not atempt to limit their circulation. Einstein's doubts, and his questions about chance and time are still the fundamental questions of our epoch."15)

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15) *Translator's note*: I have not been able to locate the original paper, and have therefore had to retranslate a Russian translation.

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