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Quantum mechanics: new experiments, new applications, and new formulations of old questions

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Contents

Abstract. **Some of the quantum mechanical conceptual problems, their current status, and related theoretical developments are reviewed. The characteristics of the entangled quantum states are analyzed, and new experiments and quantum information applications involving such states are discussed. The well-known paradox of Schrödinger's cat (the impossibility of observing superpositions of macroscopically distinct states that are predicted by quantum mechanics) is discussed. It is shown that decoherence (arising when a quantum system is measured in such a way that some information about its state is recorded in its environment) prevents the distinguishing of a superposition and the corresponding mixture. This overcomes the difficulties associated with the paradoxical nature of quantum measurement provided we remain within the framework of the theory of open systems. Other conceptual difficulties, while actually lying outside physics, are now the subject of much research and have already led to new interesting interpretations of quantum mechanics. The suggestion of Wigner and others that the observer's consciousness be included in the theory of quantum measurement is discussed in this context. A hypothesis is put forward which might enable the functioning of consciousness to be described in quantum measurement terms.**

¶ The author is also known by the name M B Mensky. The name used here is a transliteration under the BSI/ANSI scheme adopted by this journal.

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From the Editor. The advent of the theories of relativity and quantum mechanics has had a great impact on physics, and has naturally touched fundamental philosophical (epistemological, gnoseological) issues. As regards relativity (leaving aside the closely related cosmology and, to some extent, black holes), its foundations are practically no longer debated. By contrast, quantum mechanics, its methodological basis, the theory of measurements and other aspects are still actively discussed in world literature. And indeed, the advances in experimental techniques have made it possible to perform a number of most exquisite experiments (quantum teleportation being just one example).

In the past in the USSR the foundations of the new physics were also much discussed, but, unfortunately, subject to considerable ideological restrictions. To wit, one had to pay genuine or at least formal homage to a philosophical doctrine known as dialectical materialism. This made free discussion impossible, and the issues of methodology of physics of the present-day level practically disappeared from Russian publications. This is felt even now, in spite of the fact that anyone today in Russia is completely free to engage in scientific discussion of methodological and, in particular, gnoseological matters. This paper by M B Menskiĭ is a good example of the scientific treatment of the foundations of quantum mechanics not restricted by dogmas of any kind. We hope that this will stimulate other authors to openly express their opinions in presentations and letters to the Editor, without any ideological proscriptions. Of course, we are not referring to speculations that ignore the recognized content of modern physics, and in particular, quantum mechanics.

1. Introduction

Quantum mechanics has long become an everyday working tool for researchers in many different fields of physics. At the same time, certain conceptual points that were at issue from the early days of quantum mechanics have not been resolved even to this day. The well known examples are the Einstein – Podolsky – Rosen (EPR) paradox and the paradox of Schrödinger's cat. The not solved yet conceptual problem of quantum mechanics are often jointly referred to as 'problem of measurement'. Unlike other physical problems, they lack a straightforward and clear formulation, and are often presented in different ways by different authors. Moreover, many established scientists claim that there are no conceptual problems in quantum mechanics whatsoever. Attempts to raise these questions are often met with admonishment and reproof. A typical comment is that this is philosophy not physics, and the word 'philosophy' clearly rings with condescension.

In recent years, however, this attitude to the conceptual problems of quantum mechanics has been changing rapidly. In spite of the fact that they were discussed extensively in the pubertal years of quantum mechanics (see, for example, reprints of classic papers in Ref. [1]), and at all times were systematically highlighted in textbooks (see, for example, Refs [2 – 5]), today there is a vast body of literature dedicated to these problems. They are discussed today in much greater detail than before, and this discussion is gradually becoming a fairly respectable occupation (see, for example, Refs [6 – 15]). Moreover, the old issues known from the times of the founding fathers receive new formulations, special experiments are carried out to get answers, and discussions germinate new applications of quantum mechanics. In this paper we try to illustrate the current state of affairs, without attempting to give a full coverage and admitting a certain subjectivity of views expressed.

We observe from the outset that the new applications generically referred to as 'quantum information' emerged not so much from the studies of conceptual problems of quantum mechanics as from the comparative analysis of quantum theory versus classical. Of course, the analysis of the specific quantum aspects is a necessary preliminary stage in the study of conceptual problems. However, new applications begin to arise at a level of analysis when it is too early yet to speak of conceptual problems or paradoxes. One may well say that the work on new experiments and new applications is real physics, and very interesting at that, while the paradoxes of quantum mechanics are just a philosophical (conceptual, metaphysical) superstructure.

One of the aims of this paper is to show that this is indeed the case. More precisely, we are going to demonstrate that a formulation of quantum mechanics is possible where there are no paradoxes, and which supplies answers to all the questions usually asked by physicists. Paradoxes only arise when the inquirer is not content with the 'physical' level of the theory, when he poses such questions that are not customarily asked in physics — in other words, when he takes the liberty of going beyond the frontiers of physics. It is quite reasonable to believe that such attempts on the part of the physicist have little sense.

Those who think that way must not be blamed. They may even be right, because constructive work in physics requires well posed purely 'physical' problems. Some researchers, however, find it necessary to go beyond the limits of the proper physical methodology, and to define a broader scope of questions. It is then that the quantum paradoxes come to light. As it turns out, attempts to resolve these paradoxes often lead to remarkable new conceptions, which are at least very interesting. Admittedly, not much progress has been made in this direction. Nevertheless, the charm and boldness of the emerging picture of the quantum world allow one to believe that this avenue will eventually lead the theory up to a new level. A possible concretization of this hope, which we are going to defend, consists in that the new theory may include (and possibly explain) the phenomenon of consciousness — which still remains a mystery.

So, in the forthcoming sections we shall analyze two basic specifically quantum concepts: entangled states, and Schrödinger's cat. Most space (Sections 2 and 3) will be given to the analysis of specific features of quantum mechanics (as compared to the classical theory) related to these concepts, and to the new physical situations that follow. We shall discuss the schemes of 'quantum information' based on entangled states, and the phenomenon of decoherence [1] that prevents the observability of the macroscopic Schrödinger's cat (superpositions of macroscopically distinct states).

In Section 4 we briefly discuss the paradoxes and conceptual issues of quantum mechanics that cannot be resolved within the framework of decoherence. The questions we try to answer are:

— Is it necessary to ask these 'eternal' questions?

— Can they be answered within the realm of physics?

— Are there answers to these questions beyond the limits of physical theory?

We shall arrive at conclusions that are not new, but have not yet been universally accepted:

— From a practical standpoint these questions are not necessary.

— They cannot be resolved (and should not be posed) within the framework of physics.

— If a solution does exist, its formulation will in some way or other include such a 'nonphysical' element as the mind of the observer.

Finally, we formulate and try to substantiate the hypothesis that may explain the phenomenon of consciousness in terms of the quantum theory of measurements.

2. Entangled states

Quantum correlation, or the entangled states (also known as EPR states) may arise in a system that consists of two or more interacting subsystems. There is no entanglement arise when the system occurs in the state of the form $|\Psi\rangle = |\psi\rangle|\varphi\rangle$, where $|\psi\rangle$ and $|\varphi\rangle$ are the states of respective subsystems. Such a state is referred to as factorized. However, even if in the beginning the state is factorized, it may become entangled after the subsystems interact with one another. The simplest entangled state has the form [2]

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\big(|\psi_1\rangle|\varphi_1\rangle + |\psi_2\rangle|\varphi_2\rangle\big) . \tag{1}$$

Obviously, if the entire system occurs in state (1), the state of each subsystem is not determined. There is only a correlation

[1] The modern description of decoherence derives from the work of a range of physicists including Murray Gell-Mann, Jim Hartle, Stephen Hawking, Erich Joos, Dieter Zeh, Wojciech Zurek, and others. Selective description of decoherence by restricted path integrals was proposed by Menskiĭ, see below). (*Author's note to the English edition*.)

[2] In the general case the entangled state includes more than two components, $|\Psi\rangle = (1/\sqrt{n})\sum_i |\psi_i\rangle\varphi_i\rangle$. The set of components of the superposition can even be continuous.

which may be described as follows: if one subsystem occurs in state $|\psi_i\rangle$ $(i = 1, 2)$, then the other occurs in state $|\varphi_i\rangle$.

2.1 Nonclassicality of the EPR pair

The feasibility of entangled states leads to certain features of quantum systems that have no analogs in classical physics and therefore seem very strange to the intuition developed in the analysis of classical systems. Situations of this kind were analyzed in the work of Einstein, Podolsky and Rosen [16]. It turned out that the concept of the 'element of reality' in the classical sense is not applicable to the quantum theory. This contradiction between quantum mechanical predictions and classical intuition became known as the Einstein–Podolsky–Rosen (EPR) paradox.

This paradox was at the center of the famous debate between Einstein and Bohr (see Ref. [17]), and was later much discussed in literature. In 1964 John Bell proposed a simple and clear formulation of this paradox in terms of the so-called Bell inequalities (see Ref. [6]), which we shall discuss here in general terms.

The simplest way to carry out such an analysis is to use the example of the decay of a particle with spin 0 into two particles with spin 1/2. The state of the two particles after such decay is [3]

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_1|\downarrow\rangle_2 - |\downarrow\rangle_1|\uparrow\rangle_2\right), \tag{2}$$

where $|\uparrow\rangle_i$ denotes the state of ith particle with its spin directed upwards with respect to the selected axis (say, z), and $|\downarrow\rangle_i$ denotes the state of ith particle with downward spin. Evidently, state (2) is an entangled state of the two particles; the direction of spin of each particle is not determined, but there is quantum correlation between the directions of the spins of the two particles.

As a result of this correlation, measurements of the projections of the spins of the two particles are correlated even when the particles have traveled far away from each other. If the measurement of spin projection of the first particle shows that the spin is directed upwards, then the spin of the other particle is directed downwards no matter how far away that particle is, and vice versa.

There is nothing peculiar or specifically 'quantum' in this situation. A similar correlation between the results of measurements of two objects may well exist in classical physics as well. Assume, for example, that there are two balls in a black box, one white and the other black. Let then a wall be placed in the box that separates the balls, and two halves of the box, each containing one ball, are moved far away from each other. Obviously, when these half-boxes are opened, the results are correlated: if one contains the white ball, the other has the black one, and vice versa.

The specifically quantum features arise when we measure the projections of the spins of two particles onto different axes. For example, we measure the projection of the spin of the first particle onto the z axis, and the projection of spin of the other particle onto an axis inclined with respect to z. If we find that the spin of the first particle is directed upwards (in the positive sense of the z axis), it is not possible to predict for certain the result of the other measurement. However, the conventional quantum mechanical rules can be used to determine the probabilities of the two alternative results of measurement. And it turns out that the results of quantum mechanical calculations are incompatible with the assumption that the observed properties had existed before the measurement.

Bell introduced the concept of the 'objective local theory', in which the properties of the system (in our case the particle) objectively exist irrespective of the measurement, and which includes some other principles characteristic of the classical theory. Namely, in the objective local theory

— each particle is characterized by a number of variables (which may correspond, for instance, to the wave function), which are possibly correlated for the two particles;

— the results of measurement of one particle do not depend on whether the other particle is measured or not, and if it is, they do not depend on the result of such a measurement;

— the characteristics of statistical ensembles (and therefore the statistics of measurement) depend only on the conditions that existed at earlier times: 'retrospective causality' is not possible.

Bell's theorem [6] proved in 1964 states that the objective local theory and quantum mechanics give different predictions as to the statistics of the results of measurements. More precisely, the axioms of the objective local theory lead to certain inequalities (Bell's inequalities) for the probabilities of different results of measurements, and quantum mechanics predicts that these inequalities are violated when the projections of spin onto different axes are measured for the two particles.

After the formulation of Bell's theorem, attempts were made to experimentally verify Bell's inequalities, and in 1980 Aspect experimentally demonstrated that Bell's inequality is violated (see Ref. [18]) [4]. This result agrees with quantum mechanics and disagrees with the objective local theory. This was experimental proof of the fact that it is not (or at least not always) possible to treat the states of microscopic systems as objective reality independent of the measurements performed. Later there were many more correlation experiments of the type that Aspect carried out.

Aspect's experiments, like any experiments with EPR pairs, are also interesting because they demonstrate so-called 'quantum nonlocality': the measurement applied to one of the particles predetermines the outcome of a measurement carried out on the other particle at the same time and at a different location. Two events (measurement of the first particle and measurement of the second particle) may be separated by a spacelike interval, and still one measurement predetermines the result of the other. To make this circumstance even more convincing, experiments similar to those performed by Aspect have been carried out with an ever increasing distance between the particles. Recently the group led by N Gisin in Geneva set up a correlation experiment [19] with a distance of 10 km between the two particles of the EPR pair. The outcome of the experiment was the same.

At first glance it may seem that causality is violated in these experiments. This is not the case, however, because the relationship between the two events (measurement of the first

[3] The minus sign in this expression ensures that the state of the two particles is singlet rather than being a component of triplet state — corresponding to total spin 0 rather than 1.

[4] These experiments used polarized photons rather than particles with spin 1/2, and it was the polarization of the photon that was measured, not the projection of the spin. However, the calculation for such a measurement is essentially the same as that used for spin projection.

particle and measurement of the second particle) is a correlation rather than the relationship of cause and effect. Even though there is a correlation between the results of measurements of the two particles, the statistics of measurement of a single particle bears no trace of such a correlation: the projection of the spin (onto any axis) at each measurement is positive with probability $1/2$ or negative with the same probability. The experimenter has no control over the results of measurements, and hence cannot send a signal to the point where the other particle is located. Faster-than-light transmission of a signal is not feasible.

The impossibility of faster-than-light communication implies that 'quantum nonlocality' has a special correlation nature. The nonlocality of the results of measurements arises when we have an EPR pair (two particles in an entangled state). However, the creation of such a pair is a local process. The fact that preparation of quantum nonlocality is by itself a local process will become clear in Section 2.2.1 where we discuss quantum teleportation. Another illustration is the consideration [20] of an EPR pair of spin particles in the gravitational field that rotates the spin of the particles. In this case there is no global direction in space onto which the spin could be projected. The correct description of the correlation requires defining spacial directions at the point where one of the particles is found, and defining the directions at the location of the other particle by parallel transport along the world lines of the particles [5].

In experiments like those carried out by Aspect, the objective local theory is ruled out by observations in which the statistics of outcomes of measurements performed on the EPR pair are measured. Greenberger, Horn and Zeilinger proposed a more sophisticated correlation experiment with three photons (see Ref. [21]), in which the results of measurements as predicted by the objective local theory differ more radically from the predictions of quantum theory: for a certain measurement the objective local theory predicts a positive result, whereas quantum mechanics predicts a negative result (and the latter is confirmed experimentally).

2.2 Applications: quantum information

The properties of entangled states and some other characteristic features of quantum mechanics have found their way into new practical applications of quantum mechanics known as quantum information [22–25]. These applications are being developed in three major categories:

— quantum teleportation,
— quantum cryptography,
— quantum computers.

The main results in the field of quantum information are expressed in terms of qubits (from 'quantum bit'), a qubit being a system that may occur in either of two states, for example, $|0\rangle$ and $|1\rangle$, or in a superpositions of these states [6]. Two or more qubits may occur in an entangled state.

2.2.1 Quantum teleportation. The purpose of quantum teleportation is to transfer a certain quantum state from one point to another. This is accomplished with the aid of an EPR pair — or, in other words, by means of quantum correlation. So far (both theoretically and experimentally) the problem of teleportation of just one qubit has been considered.

Let observer A (Alice) have a qubit in the state

$$|\psi\rangle_{\mathrm{A}} = \alpha|0\rangle_{\mathrm{A}} + \beta|1\rangle_{\mathrm{A}} ,$$

where the parameters α and β are not known to the observer. Now the task is to transfer another qubit of the remote observer B (Bob) into the same state

$$|\psi\rangle_{\mathrm{B}} = \alpha|0\rangle_{\mathrm{B}} + \beta|1\rangle_{\mathrm{B}} .$$

To do this, qubit B has to be in a certain way correlated — that is, included into the EPR pair. For example, at point B one may create an EPR pair of two qubits, C and B, and then move qubit C to the location of observer A (alternatively, an EPR pair of two qubits can be created at an arbitrary point in space, and then move one qubit of the pair to A, and the other to B). Now observer B has qubit B, and we only need to bring it into the required state. This is accomplished in three steps:

(1) A certain specially designed measurement is performed on the system consisting of qubits A and C. Such a measurement may give 4 different results.

(2) The result of measurement is transmitted (through a conventional — that is, classical — communication channel) to point B.

(3) The state of qubit B (that arises after the measurement performed at point A) is subjected to one of four transforms depending on the outcome of the measurement.

It is easy to show that teleportation according to this scheme is possible. For this, it will suffice to take the state of EPR pair of the form

$$|\Phi\rangle_{\mathrm{CB}} = \frac{1}{\sqrt{2}}\big(|01\rangle_{\mathrm{CB}} - |10\rangle_{\mathrm{CB}}\big) = \frac{1}{\sqrt{2}}\big(|0\rangle_{\mathrm{C}}|1\rangle_{\mathrm{B}} - |1\rangle_{\mathrm{C}}|0\rangle_{\mathrm{B}}\big)$$

and at the first step perform a measurement on qubits A and C that is described by the projectors [7]

$$P_1 = \frac{1}{2}\big(|01\rangle_{\mathrm{AC}} - |10\rangle_{\mathrm{AC}}\big)\big({}_{\mathrm{AC}}\langle 01| - {}_{\mathrm{AC}}\langle 10|\big) ,$$

$$P_2 = \frac{1}{2}\big(|01\rangle_{\mathrm{AC}} + |10\rangle_{\mathrm{AC}}\big)\big({}_{\mathrm{AC}}\langle 01| + {}_{\mathrm{AC}}\langle 10|\big) ,$$

$$P_3 = \frac{1}{2}\big(|00\rangle_{\mathrm{AC}} - |11\rangle_{\mathrm{AC}}\big)\big({}_{\mathrm{AC}}\langle 00| - {}_{\mathrm{AC}}\langle 11|\big) ,$$

$$P_4 = \frac{1}{2}\big(|00\rangle_{\mathrm{AC}} + |11\rangle_{\mathrm{AC}}\big)\big({}_{\mathrm{AC}}\langle 00| + {}_{\mathrm{AC}}\langle 11|\big) .$$

With this selection of EPR pair and measurement, the adjusting transforms U_i to be performed at the third step must have the form

$$U_1 = 1 , \qquad U_2 = |0\rangle\langle 0| - |1\rangle\langle 1| ,$$
$$U_3 = |0\rangle\langle 1| + |1\rangle\langle 0| , \qquad U_4 = i\big(|0\rangle\langle 1| - |1\rangle\langle 0|\big) .$$

If the measurement gives the ith result, the state that arises after the measurement is (up to a normalization coefficient)

[5] Moreover, the correlation is somewhat 'blurred' because the world lines of quantum particles are defined only approximately.

[6] Examples are the states of a particle with spin $1/2$ with a definite projection onto a selected axis, the state of a photon with one of the two possible orthogonal polarizations, or the states of a two-level system with a definite energy.

[7] The change of state of the measured system at ith result of measurement is described by the action of projector P_i. The squared modulus of the resulting vector is the probability of ith result of measurement.

$P_i|\psi\rangle_A|\Phi\rangle_{CB}$. Then it is easy to show that qubit B assumes a definite state $|\psi_i\rangle_B$ determined by coefficients α and β and number i. This state is identical to the initial state $|\psi\rangle_A$ only if $i = 1$. However, we know how to get the required state of qubit B for arbitrary i: the state $|\psi_i\rangle_B$ after the measurement must be subjected to transformation U_i. Then qubit B assumes the required state

$$U_i\,|\psi_i\rangle_B = |\psi\rangle_B\,.$$

Observe that qubit A after these operations does not occur in any definite state. Instead we have an entangled state of qubits A and C.

Thus, in the case of quantum teleportation the arbitrary (and not known in advance) state of qubit A is destroyed, but at another point qubit B assumes an identical state. The instrument of teleportation is the EPR pair with the components at points A and B, which essentially forms a quantum correlation line. In addition to this correlation line prepared in advance, we also need a conventional communication channel between points A and B to transmit information about the result of measurement of qubits A and C.

Teleportation is carried out in three steps. At the first (preparatory) step the correlation line (EPR pair) is created. At the second step, the qubits A and C are measured. The 'quantum part' of information about the state $|\psi\rangle$ is instantaneously transmitted from point A to point B by means of quantum correlation. Reconstruction of this state at point B, however, also requires classical information that can be transmitted not faster than the speed of light.

It is true that when the result of measurement is $i = 1$, the state $|\psi\rangle$ is teleported instantaneously, at the time of measurement, and no additional adjustment is required. But the experimenter at point B does not know which of the four possible results was obtained at point A, and so at every measurement it is not known whether any deformation of state has occurred during teleportation that has to be corrected. This leads us to conclusion that faster than light teleportation is not possible even when the correlation line is prepared in advance.

Quantum teleportation was experimentally realized at Innsbruck University [26] with polarized photons as qubits. For more details see review [25] [8].

2.2.2 Quantum cryptography. We saw that in the case of teleportation of a quantum state from one point to another the state of qubit at the initial point is destroyed. This is one of the implications of the general theorem stating the impossibility of 'cloning' a quantum state. This theorem follows from the linear nature of quantum mechanics. Any process in quantum mechanics is described by a unitary linear operator. Cloning — had it been possible — would have been described by the transform

$$U|\psi'\rangle|A\rangle = |\psi'\rangle_1|\psi'\rangle_2|A'\rangle\,,$$

where $|A\rangle$, $|A'\rangle$ denote the states of the apparatus before and after cloning, respectively. Writing such equations for two different states of the system $|\psi'\rangle$, $|\psi''\rangle$, and taking advantage of the linearity of operator U, we get for the superpositions of these states

$$U\big(\alpha|\psi'\rangle + \beta|\psi''\rangle\big)|A\rangle = \alpha|\psi'\rangle_1|\psi'\rangle_2|A'\rangle + \beta|\psi''\rangle_1|\psi''\rangle_2|A''\rangle\,.$$

Obviously, a superposition of two (nonidentical) states $|\psi'\rangle$, $|\psi''\rangle$ cannot be cloned: even when $|A'\rangle = |A''\rangle$, then state $\alpha|\psi'\rangle + \beta|\psi''\rangle$ becomes $\alpha|\psi'\rangle_1|\psi'\rangle_2 + \beta|\psi''\rangle_1|\psi''\rangle_2$, which is not the same as

$$\big(\alpha|\psi'\rangle_1 + \beta|\psi''\rangle_1\big)\big(\alpha|\psi'\rangle_2 + \beta|\psi''\rangle_2\big)\,.$$

The impossibility of cloning a quantum state is the principle of quantum cryptography. A quantum cryptographic device sends a sequence of photons down the waveguide, useful information being encoded in the polarizations of photons in the stream. Had cloning been possible, one could penetrate into the waveguide and copy the information (create, for example, an identical sequence of photons) without altering the states of photons that fly down the waveguide. Since cloning is impossible, however, any attempt to get the information (intercept the message) leads to distortion of the state of photons moving in the waveguide. Special data processing protocols use this distortion to detect eavesdropping with any desired probability.

In this way, the specific features of quantum mechanics allow the construction of communication channels with any desired degree of protection against eavesdropping (for more details see Ref. [25]).

2.2.3 Quantum computing. The idea of the quantum computer [22, 24] is based on the feasibility of superpositions of quantum mechanical states. A quantum system with two basic states (a qubit) allows the numbers 0 and 1 to be encoded in these states $|0\rangle$, $|1\rangle$. Accordingly, a chain of n qubits, each of which occurs in one of the two possible states, represents an n-digit binary number. Now if each qubit in the chain occurs in a superposition of basic states $(|0\rangle + |1\rangle)/\sqrt{2}$, then the state of the entire chain of qubits may be described as a superposition of 2^n binary numbers of length n. A sequence of unitary transforms applied to such a chain realizes a certain procedure of processing of information (represented as binary words), and all 2^n sets of inputs will be processed in parallel.

This is the realization of 'quantum parallelism', which allows certain calculation processes to be made much more efficient than is possible with a classical computer. Problems that take an exponentially long (which means practically infinite) time with a classical computer may be solved by quantum computer over a polynomially long time, which for some practically important tasks is quite feasible [9].

[8] B B Kadomtsev and M B Kadomtsev (see, for example, Refs [27, 11]) suggested that the Sokolov effect, as yet not explained (the polarization of a hydrogen atom flying along a metallic surface [28]) may be due to quantum correlation between the atom and the immense number of electrons in the surface layer of metal. This could have been another very interesting manifestation of entangled states; in our opinion, however, the authors fail to give convincing proof that the effects of EPR pairs formed by the atom with different electrons add up in a coherent fashion (which is necessary for the effect to be reasonably strong). So this matter calls for additional consideration. We also doubt the conclusion made in Ref. [11] that the Sokolov effect can be used for communication faster than light.

[9] Exponential or polynomial with respect to the length n of binary numbers processed.

According to the above, the state of a quantum computer is a sum of an immense number of terms, each of which is a product of states of the form $|0\rangle$ or $|1\rangle$ (the terms in this product describe the possible states of individual qubits in the long chain). Accordingly, the state of a quantum computer is nothing else but a very complicated entangled state. After a series of unitary transforms that rearrange this state in accordance with the set task, the resulting state is measured, and the result of this measurement is actually the goal of the calculation. We see that the work of a quantum computer is based on operations with complex entangled states of a chain of qubits.

Operations of this kind can be used, for example, for finding the period of a periodic function, or for factorizing very large numbers. The latter possibility is especially valuable, because it would allow the easy breaking of ciphers currently used. In principle, this can also be accomplished with classical computers, but takes such a long time as to be totally impractical.

Of course, there are immense difficulties in the way of constructing quantum computers which operate with numbers that are long enough. First of all, one has to ensure quantum coherence of a very large number of qubits (which can be represented by different physical systems — for example, atoms). This requires preventing (or making extremely small) any uncontrollable interactions of qubits with one another and with the environment. In Section 3.3 we shall demonstrate how interactions lead to decoherence (the loss of coherence).

The difficulties here are so formidable that they may even turn out to be insurmountable. For example, it may turn out that the realization of quantum computation requires making the uncontrollable interactions exponentially small, which is hardly possible. So far, however, quantum computers are regarded to be feasible in principle, and considerable resources are being allocated to the solution of this task. The idea of a quantum computer is discussed at greater length in paper [25].

2.3 Quantum mechanics at a new stage

To conclude the section of entangled states, let us make a few more remarks. The specific features of quantum mechanics related to entangled states were first formulated in connection with the EPR paradox; today, however, they are no longer regarded as paradoxical. For the people who work professionally with the quantum mechanical formalism (that is, for most physicists), there is nothing paradoxical either in EPR pairs, or in the most complicated entangled states with a large number of terms and a large number of factors in each term. The results of any experiments with such states, in principle, are readily interpretable (although technical difficulties in the calculation of complex entangled states are of course possible).

The disappearance of the feeling of paradoxicality is explained by the fact that the specifics of the entangled states, known from the early days of quantum mechanics, have been studied over the years in considerable detail. In particular, some features were formulated as straightforward and clear statements or theorems, such as the impossibility of cloning of states. Going into detail also gave rise to new applications of quantum mechanics — quantum information.

The process of active and detailed study of the specific features of quantum mechanical states and quantum measurements over the past two decades was obviously fostered by the development of new experimental capabilities, with the great sensitivity of today's instruments. The increased sensitivity of measurements has brought about a situation in which many more experimenters have to use quantum mechanics in their daily work (see, for example, Ref. [29]). This gave rise to new branches of science — such as quantum optics, for example. People working in these new fields have developed useful analogies and straightforward definitions, which allow students or beginners quickly to 'get the hang' of quantum mechanics, to learn to find the correct approaches to the tasks typical of their particular field. The availability of plain language facilitated the development of physical intuition.

Concurrently and in close connection with the process of 'assimilation' of quantum mechanics by a much greater number of physicists and engineers than ever, its old applications (such as superconductivity) and entirely new ones (quantum information) were being developed. Day-to-day experience with quantum mechanics stripped many of its features (like the superposition of states, the entangled states) of the aura of paradoxicality.

However, quantum mechanics still has certain aspects which possess some weirdness and paradoxicality, and which for this very reason may be the new point of growth in quantum theory. Let us discuss these aspects.

3. 'Schrödinger's cat'

As is known, the space of states of a quantum mechanical system is linear. This means that, along with any two of its states $|\psi_1\rangle$, $|\psi_2\rangle$, the linear combination (superposition) $c_1|\psi_1\rangle + c_2|\psi_2\rangle$ with arbitrary (complex) coefficients c_1, c_2 is also possible. For example, if a point particle may occur at either of two points, it may also occur 'at both points at the same time'. There is nothing like that in classical mechanics. The space of states of a classical system is not a linear space. A classical system may occur in one of the possible states, but there is no meaning in the sum of its states. For example, a stone may occur either at one point, or at another, but not at both points at the same time. Of course, here the points are finite regions whose dimensions are small compared with the distance between them.

As applied to microscopic objects (particles or atoms), the feasibility of superpositions of states has long ceased to surprise anyone. Moreover, the existence of superposition has long been proved experimentally. A classic example is the famous two-slit experiment — the interference pattern from a beam of particles passing through two slits in an opaque screen. On the other hand, it is hard to conceive a superposition of macroscopically distinct states of a macroscopic body (for example, two possible locations of a stone).

As a matter of fact, however, these two statements come into contradiction which arises from the possible 'amplification' which converts a superposition of two microstates into a superposition of two macrostates. Such amplification takes place in the case of quantum measurement — that is, any measurement applied to a quantum system.

This contradiction or paradox was clearly expressed by Schrödinger in his mental (thought) experiment known as 'Schrödinger's cat'.

3.1 Superposition of an alive and dead cat

The decay of an unstable quantum system (for example, radioactive atom) is governed by an exponential probability law. Over a time much longer than the half-life of the isotope, the decay will occur with certainty. This means that over this time the state $|\psi_1\rangle$, corresponding to the nondecayed atom, will go over into the state $|\psi_2\rangle$, which describes the decayed atom and the products of its decay. At any intermediate time, however, the state of unstable atom is described as a superposition $c_1|\psi_1\rangle + c_2|\psi_2\rangle$ of states of the nondecayed and decayed atom (the coefficient c_1 decreases with time, and c_2 increases).

This is not surprising since we are talking about a microscopic system (atom), and superpositions of states for microscopic systems are possible. Assume now that the products of decay are registered, for example, by a Geiger counter, which activates a relay that switches a macroscopic device. In order to dramatize the situation and add spice to his reasoning, Schrödinger suggested placing the atom together with Geiger counter into a box where there is a cat, an ampule with cyanide, and a device that breaks this ampule. When the atom decays and the counter clicks, the device is activated and breaks the ampule — the poor cat dies. All is clear for times much longer than the atom's half-life: the cat is dead. When the time is close to the atom's half-life, however, the atom is in a superposition of the decayed and nondecayed state. But this means that the cat is a superposition of an alive and dead cat!

So there is a contradiction between the conclusion (the necessity of superposition) to which we arrived by logical reasoning, and the observation that can hardly be doubted: the cat can be either alive or dead, but nobody has ever seen anything like a superposition of these two states.

This conclusion can be reformulated or refined. Whenever we open the box, we see either an alive cat (and this means that the atom has not decayed) or a dead cat (which means that the decay has occurred). Before we open the box, however, the logic of quantum mechanics makes us believe that the system (atom + cat) occurs in a superposition of two states (nondecayed atom + alive cat) and (decayed atom + dead cat). The paradox consists in that the description of the situation depends on whether we have opened the box to see what is inside, or not.

3.2 'Amplification' of quantum superposition

All that is placed in the box apart from the atom itself serves the purpose of 'amplification' that converts the superposition of states of the microscopic system into a superposition of states of the macroscopic system. Such amplification occurs in any quantum measurement. The mechanism of amplification consists in the formation of an entangled state which includes a macroscopic number of subsystems (or degrees of freedom). Let us explain this.

Amplification involves the interaction of the quantum system (which occurs in the state of superposition) with other systems (or degrees of freedom), which causes entanglement (quantum correlation) with the latter. Then the initial system and the newly entangled systems all interact with a greater number of systems, bringing them into the entangled state. This goes on until there is an entangled state that involves a great number of systems, or at least a great number of degrees of freedom. If such processes involve a sufficient number of degrees of freedom, then the resulting state can only be interpreted as a superposition of macroscopically distinct states of the macroscopic system. Let us now describe this in the language of mathematical equations. Assume that the microscopic (and therefore by all means quantum) system ψ occurs in the state of superposition $c_1|\psi_1\rangle + c_2|\psi_2\rangle$. Now assume that this system has interacted with some other system α. For the given initial state $|\alpha_0\rangle$ of system α, the result of interaction depends on the state of system ψ. We are going to consider only such an interaction which leads to the distinguishing between the states $|\psi_1\rangle$ and $|\psi_2\rangle$, without changing these states. It is this kind of interaction that is typical of processes which may be referred to as measurements (in this particular case it is the measurement characterized by projectors $|\psi_1\rangle\langle\psi_1|$ and $|\psi_2\rangle\langle\psi_2|$). 'Distinguishing' means that the final states of the system α, corresponding to the initial states $|\psi_1\rangle$ and $|\psi_2\rangle$ of system ψ, are different. The transition described by this interaction may be described as

$$|\psi_1\rangle|\alpha_0\rangle \to |\psi_1\rangle|\alpha_1\rangle\,, \qquad |\psi_2\rangle|\alpha_0\rangle \to |\psi_2\rangle|\alpha_2\rangle\,.$$

Here the arrow replaces the action of unitary operation that describes the evolution. Then, however, by virtue of the linearity of this operator, the initial state $c_1|\psi_1\rangle + c_2|\psi_2\rangle$ of system ψ causes the transition

$$\big(c_1|\psi_1\rangle + c_2|\psi_2\rangle\big)|\alpha_0\rangle \to c_1|\psi_1\rangle|\alpha_1\rangle + c_2|\psi_2\rangle|\alpha_2\rangle\,.$$

In this way, the interaction gives rise to the entangled state of systems ψ and α.

Assume now that the interaction involves a large number of systems (or degrees of freedom) $\alpha, \beta, \gamma, \ldots, \omega$. The initial (measured) system ψ does not necessarily interact with each of these systems. It may interact with just some of these systems, and the systems that have interacted with system ψ will subsequently interact with the rest (and with one another). What is important is that in some way or other the information about the system ψ will be recorded in the states of all the other systems involved. As before, we assume that the state of system ψ does not change, and the states of all other systems depend on this state in such a way that they make a distinction between the states $|\psi_1\rangle$ and $|\psi_2\rangle$. This means that the interaction causes the transition

$$|\psi_1\rangle\,|\alpha_0\rangle|\beta_0\rangle|\gamma_0\rangle\ldots|\omega_0\rangle \to |\psi_1\rangle\,|\alpha_1\rangle|\beta_1\rangle|\gamma_1\rangle\ldots|\omega_1\rangle\,,$$

$$|\psi_2\rangle\,|\alpha_0\rangle|\beta_0\rangle|\gamma_0\rangle\ldots|\omega_0\rangle \to |\psi_2\rangle\,|\alpha_2\rangle|\beta_2\rangle|\gamma_2\rangle\ldots|\omega_2\rangle\,.$$

Then, owing to the linearity of the operator of evolution, the superposition of states $|\psi_1\rangle$ and $|\psi_2\rangle$ of system ψ causes the transition

$$\begin{aligned}&\big(c_1|\psi_1\rangle + c_2|\psi_2\rangle\big)\,|\alpha_0\rangle|\beta_0\rangle|\gamma_0\rangle\ldots|\omega_0\rangle\\ &\to c_1|\psi_1\rangle\,|\alpha_1\rangle|\beta_1\rangle|\gamma_1\rangle\ldots|\omega_1\rangle + c_2|\psi_2\rangle\,|\alpha_2\rangle|\beta_2\rangle|\gamma_2\rangle\ldots|\omega_2\rangle\\ &= c_1|\psi_1\rangle\,|A_1\rangle + c_2|\psi_2\rangle\,|A_2\rangle\,. \end{aligned} \tag{3}$$

If the number of systems that take part in the interaction is macroscopically large, then there is entanglement of system ψ with the macroscopic system A, and we have a superposition of two distinct states of the macroscopic system. The states that make up the superposition are macroscopically distinct in the sense that the great number of degrees of freedom in them are described by different wave functions. Thus arises the superposition of macroscopically distinct states of the macroscopic system. Such is the mechanism of amplification referred to above.

In this way, following the conventional guidelines of quantum mechanics, we come to the conclusion that superpositions should exist for arbitrarily large systems (which have arbitrarily many degrees of freedom). Naturally, the question arises whether it might be possible to create and observe superpositions of distinct states of macroscopic systems. Sometimes this task is formulated as the creation and observation of 'Schrödinger cats'.

Obviously, what precisely is a macroscopic system is not an easy question, nor what is classical behavior [9, 30–32]. In any case, however, one can try creating superpositions for systems consisting of an increasing number of particles. The difficulty in the experimental realization of this program is that the system must be very carefully insulated — otherwise the superposition will be quickly transformed into a mixture because of decoherence (see below). For mesoscopic systems containing several particles this task has been solved [33, 34]. It has been proved experimentally that quantum mechanics applies not only to microscopic systems but also to mesoscopic systems.

It is possible to create superpositions in systems with a much greater number of particles. For example, the Josephson effect is used for setting up conditions in a superconducting ring that (according to the laws of quantum mechanics) create superposition of two currents flowing in opposite directions, each carrying about 10^{15} electrons. Such experiments agree with the predictions of quantum mechanics, but as yet none of them has given a direct proof of the existence of superposition: the results can be interpreted in terms of the 'macrorealistic' theory, in which there is no superposition but only one current, and it is not known precisely which of them. It is quite possible that direct proof will soon be obtained in more accurate experiments.

3.3 Decoherence by the environment

We saw that the amplification of quantum superposition leads to a paradox: quantum mechanics logically brings us to the conclusion that superpositions of macroscopically distinct states ought to exist, but nobody has ever observed such states. Let us once again bring up the example of Schrödinger's cat: as long as the box is closed, we can only guess what is in there; if we trust quantum mechanics, we come to the conclusion that there is a superposition of an alive and dead cat. When we open the box, however, the cat is either dead or alive — and nothing else.

This situation is seen as a paradox that calls for explanation (resolution). An attempt at explanation, dating back to Heisenberg and gaining recognition in the scientific community today, is based on the concept of decoherence.

Decoherence of a quantum system occurs every time its state gets entangled with the state of its environment, so that the information about the state of the system is 'recorded' in the state of its environment. Let us consider, for example, process (3) which transfers the initial factorized state of the system and its environment into the entangled state

$$|\Psi\rangle = c_1|\psi_1\rangle|\mathrm{A}_1\rangle + c_2|\psi_2\rangle|\mathrm{A}_2\rangle \,.$$

This is a pure state, and therefore it can be described by the vector of state (wave function). However, we can also express it in terms of the density matrix:

$$R = |\Psi\rangle\langle\Psi| \,.$$

If we are only interested in the state of the system ψ (and not its environment A), we can describe this state by the so-called reduced density matrix, which equals the trace of matrix R with respect to the degrees of freedom of the environment:

$$\rho = \mathrm{tr}_{\mathrm{A}} R = |c_1|^2|\psi_1\rangle\langle\psi_1| + |c_2|^2|\psi_2\rangle\langle\psi_2| + c_1c_2^*\langle\mathrm{A}_2|\mathrm{A}_1\rangle|\psi_1\rangle\langle\psi_2| + c_2c_1^*\langle\mathrm{A}_1|\mathrm{A}_2\rangle|\psi_2\rangle\langle\psi_1| \,. \quad (4)$$

States $|\mathrm{A}_1\rangle$ and $|\mathrm{A}_2\rangle$ are macroscopically distinct — they differ from one another in the immense number of degrees of freedom. In the notation of Eqn (3), $|\alpha_1\rangle$ differs from $|\alpha_2\rangle$, $|\beta_1\rangle$ differs from $|\beta_2\rangle$, etc. Because of this, the scalar products $\langle\alpha_1|\alpha_2\rangle, \langle\beta_1|\beta_2\rangle, \ldots$ are each less than one in magnitude. So the product of all these numbers $\langle\mathrm{A}_1|\mathrm{A}_2\rangle$ is practically zero, and the cross terms in Eqn (4) vanish.

The state of system ψ, therefore, is described by the density matrix

$$\rho = |c_1|^2|\psi_1\rangle\langle\psi_1| + |c_2|^2|\psi_2\rangle\langle\psi_2| \,. \quad (5)$$

This is a mixed state that can be interpreted as follows: the system occurs with probability $|c_1|^2$ in the state $|\psi_1\rangle$, and with probability $|c_2|^2$ in the state $|\psi_2\rangle$. This is exactly what ought to be expected after the measurement (at least for the simplest type of measurement described by von Neumann's reduction postulate). Emergence of the mixed state (5) is called decoherence. Decoherence is associated with the loss of information about the relative phase of coefficients c_1, c_2. There is extensive literature on decoherence. Important works in this field are Refs [30, 35–41]. The physical nature of decoherence is discussed in great detail and from different standpoints in the books [9, 11], where the reader will also find a comprehensive bibliography. A review of various phenomenological approaches to the description of the process of decoherence can be found in Refs [42, 43].

Two types of mixed states sometimes are distinguished that have similar density matrices: (1) proper mixed states of a closed system that arise when it is not known exactly in which of the pure states the system occurs, and (2) improper mixed states that are, like in our present case, associated with reduction — that is, arising upon transition from a closed system to its subsystem. If such a distinction is made, then it is often maintained that it is not correct to interpret improper mixtures in terms of 'incomplete knowledge', as is done for proper mixtures. Such a distinction, however, only makes sense when it is possible to control experimentally not only the system itself, but also its environment (or, in case of a closed system, to make sure that the system is closed). One cannot think of an experiment confined to the limits of a system occurring in a mixed state that would be capable of verifying whether the system is closed (so mixture then corresponds to incomplete knowledge) or open (so the mixture is a consequence of the entanglement of the system with the environment). The impossibility of experimental distinction between these two cases follows directly from the fact that the predictions of all experiments feasible in a given system are expressed in terms of the density matrix of this system.

It is important for us now that because of entanglement with the environment the system goes from the pure initial state into a mixed state. The superposition of states of the system vanishes (or at least cannot be observed) if we confine ourselves to experiments on the system alone, without touching its environment A. Another thing is also true: if the states $|\psi_1\rangle$ and $|\psi_2\rangle$ are orthogonal, then after entanglement of the system with its environment not only the system but also the environment are not in the state of superposition, but rather in a mixed state.

Applying this to the case of Schrödinger's cat, we can now describe the situation somewhat more accurately. Quantum mechanics predicts that the composite system (atom + cat) occurs in the superposition of two factorized states: (non-decayed atom + alive cat) and (decayed atom + dead cat). If we are only interested in the atom, we can only say that it occurs in a mixed state — that is, it has not yet decayed with probability $|c_1|^2$, and already has decayed with probability $|c_2|^2$. Similarly, with regard to the cat alone (forgetting the atom) we can say that it occurs in a mixed state: alive with probability $|c_1|^2$, and dead with probability $|c_2|^2$. In any case, there are no experiments which could be performed on the cat without touching the atom that could demonstrate that the actual underlying cause of the probability distribution $\left(|c_1|^2, |c_2|^2\right)$ is the superposition, and not just incomplete knowledge about the actual state of the cat (alive or dead).

If the experiments are performed on the complete system (which in our case would include both the atom and the cat), then it is in principle possible to distinguish superposition from mixture: superposition produces certain interference patterns that are absent in the case of mixture. This is of course true, but one has to bear in mind that these effects will be observed only when all the degrees of freedom of the macroscopic system (the cat) are taken into account. In any case, only a small fraction of the degrees of freedom can be left beyond the control of the measuring system, otherwise it will be not possible to distinguish between superposition and mixture.

This can be seen from model (3). If the states of some of the degrees of freedom $\psi, \alpha, \beta, \gamma, \ldots, \omega$ are left out, then to describe the state of the remaining degrees of freedom one must calculate the reduced density matrix for them, taking the trace for all degrees of freedom that are not observed. Then the cross (interference) terms in this density matrix will contain scalar products related to the degrees of freedom excluded from observation. Each of these scalar products is less than one by modulus, and if they are numerous enough, the interference terms disappear and superposition cannot be distinguished from mixture. Moreover, even if just one degree of freedom (say, ω) is left out, and the scalar product $\langle\omega_1|\omega_2\rangle$ for it is zero, superposition cannot be distinguished from mixture. When the number of degrees of freedom is macroscopic, it is of course impossible in the experiment to control all the degrees of freedom without exception. Accordingly, decoherence in macroscopic systems seems inevitable for all practical purposes.

So, the solution of the paradox of Schrödinger's cat (the impossibility of observing superpositions of macroscopically distinct states predicted by quantum mechanics) may run as follows. Even if a certain system occurs in a state described by a superposition, and then this state becomes entangled with the state of the environment in such a way that recorded in the environment is information that allows distinguishing the components of superposition, the state of the system is subject to decoherence. This means that the state becomes a mixture (not a superposition) of the same components, and there are no experiments on the system (not touching the environment that had brought about the decoherence) that can tell us whether the mixture results from a superposition, or from incomplete knowledge about which of the components actually exists. The consequence of decoherence is that the predictions of quantum theory for macroscopic states cannot be distinguished from the predictions of macrorealistic theory, unless literally all the degrees of freedom are controlled. Obviously, the number of components in superposition and in mixture is arbitrary — the case of two components has been considered here only for the sake of simplicity.

We see that the phenomenon of decoherence is very important from a conceptual standpoint. This phenomenon must also be taken into account if the effects of the environment on the dynamics of the system under consideration are not negligibly small — that is, if the system is open. because of this, much attention is paid to the study of decoherence. The role of decoherence in quantum measurements has been studied not only theoretically but also experimentally. Especially interesting are the experiments staged at Ecole Normale Supérieure in Paris [44]. The components of superposition were represented by the states of the electromagnetic field in a superconducting resonator, close to the coherent states.

The coherent state is a state ultimately close to a certain mode of classical electromagnetic field [10], and it involves a large number of photons. The states close to two modes that differed in phase were taken for the experiment. Since there were only a few photons in the cavity, the states under study were not precisely coherent, but had similar properties. Because the number of photons was not large, it was possible to form a superposition of two modes with different phases (a 'mesoscopic Schrödinger's cat'). Dissipation in the superconducting cavity is small, and the superposition persisted for a long time — during this time there was no uncontrollable decoherence. Instead, slow controlled decoherence was introduced into the system. For this end atoms were passed one after another through the cavity, where they interacted with photons and caused decoherence. This gave rise to an entangled state of photons and atoms, and information about the phase of electromagnetic field was written in the states of atoms. As a result, the superposition of modes of the electromagnetic field with two different phases gradually turned into a mixture (the process of decoherence).

In this way, the process of decoherence associated with quantum measurement has been realized and studied in a mesoscopic system. In other words, decoherence has not only been predicted theoretically, but has also been observed in experiment. It goes without saying that decoherence lifts the veil of mystery from quantum measurement. But does it completely solve the 'problem of measurement' in quantum mechanics? Some physicists still have doubts. Attempts to solve this problem in a more radical way lead to very interesting developments of quantum theory.

4. Extension of the theory of measurement

In this section we consider some variants of quantum theory of measurement that go beyond the framework of the theory of decoherence; we start, however, with a discussion of the advantages and drawbacks of this theory.

4.1 Does decoherence solve the problem of measurement?

From a practical standpoint, decoherence completely explains the process of measurement, and how the measure-

[10] To avoid confusion, please note that the word 'coherent' in 'coherent state' refers to the existence of a definite phase of the classical wave process. In all previous cases this word had a different meaning, referring to the existence of a certain relative phase between different components in the quantum superposition.

ment leads to a mixed state that is equivalent to the probability distribution with respect to various pure states corresponding to the alternative results of measurement. Interpretation is given in the framework of quantum mechanics of the closed system; at the last stage, however, the treatment is limited to a certain subsystem, and averaging is carried out with respect to degrees of freedom which are left out of this subsystem. It is this averaging that leads to a mixed state. If instead of a subsystem we consider the entire closed system, we have superposition in place of mixture — which, as we have demonstrated, leads to the paradox of Schrödinger's cat.

Thus, the interpretation of quantum measurement in terms of decoherence may be regarded as quite adequate as long as we agree to consider only open systems, and never deal with closed systems. As a matter of fact, there is nothing unnatural in such a convention. What is more, it is quite in the spirit of physics: in physics we are taught to ask only those questions that can be answered by observation (measurement), and measurement is not capable of controlling each of the macroscopic number of degrees of freedom.

If the measurement is described in terms of an open system, this system can be as broad as desired, but there still have to be some degrees of freedom outside in which information about the result of measurement will be recorded in one way or another. This condition is characteristic of quantum measurement, and corresponds to the well known arbitrariness in dividing the entire Universe into the measured system and the measuring instrument. One may call the instrument everything except the system that is being measured; or one may include some part of the apparatus into the measured system, calling the measuring device only the recorder (needle); or else the needle can also be considered part of the measured system, then the measuring device begins with the photons entering the eye of the observer, etc. The measured system can be made broader and broader, but something must always be left out that carries information about the state of the measured system. Since the observer, his brain, the mechanisms of memory etc. are usually not included into consideration with the framework of physics, we come to the conclusion that all proper physical questions can be formulated and solved within the framework of the theory of open systems using the mechanism of decoherence. As we have found out, the conceptual issues of quantum mechanics receive adequate treatment in the context of such an approach.

This approach is actively being developed in particular in the direction of description of more and more complicated measurements. Also considered are continuous (prolonged in time) quantum measurements. The problems associated with this approach are more technical than conceptual. The efforts are aimed at the construction of a consistent theory of open (measured) systems (see, for example, the review [42] and the book [43]). One may distinguish two essentially different levels of description of such systems: nonselective and selective. The nonselective description takes into account all possible results of measurement, each of which is associated with a certain probability. The behavior of the measured system is then described by a density matrix which contains both the alternative pure states and the distribution of probabilities with respect to these states. In the case of selective description the task is formulated differently: how does the system behave when the measurement yields one outcome out of all possible results? In this case the behavior of the system is described by the vector of state (the wave function) which depends on the result of measurement. Obviously, for a one-time measurement (which is the kind of measurement considered so far) the difference between these two descriptions is not large. If, however, the measurement is repeated many times, and we want to follow the change in the state of the system caused by this series of measurements, these two approaches are technically much different (while the physical content of the process naturally remains the same). This is even more true in case of continuous measurement.

So, the theory of open systems permits the description of quantum measurements without running into conceptual difficulties. For some people, however, this is not enough, and they want to go further and improve the quantum theory. Motives differ: some believe that of first importance is the theory of closed systems, whereas open systems only ought to be regarded as subsystems of the closed ones. Others are worried by the fact that improper mixtures cannot be interpreted in terms of incomplete knowledge (as done in Section 3.3), and so they are not convinced by the argument supposed to prove the indistinguishability of superpositions and mixtures in the case of decoherence. As a matter of fact, this reasoning implies that the researcher is not content with the description of an open system, and wants the description to include the environment (where the answer to the question whether the mixture is proper or improper lies). This also assumes a description in terms of a closed system.

In our opinion, the most stimulating motive for going further than the theory of decoherence is the following: the theory of decoherence adequately explains the existence of different alternative results of measurement, each with its own probability, but it is desirable to have a theory that explains *how one of these alternatives is selected.*

4.2 Attempts to advance the theory

The most straightforward attempt to advance the theory of quantum measurements is the hypothesis of *spontaneous decoherence* [45]. In this theory the Schrödinger equation is modified by the inclusion of a stochastic term that accounts for spontaneous decoherence. In other words, decoherence according to this theory is not caused by interaction between the system and its environment, but occurs spontaneously from time to time without any external influence. This raises decoherence to the rank of a fundamental law of nature. The parameters of the modified Schrödinger equation are adjusted so that on the microscopic level its predictions coincide with the predictions of quantum mechanics, but there are no superpositions of macroscopically distinct states on the macroscopic level. With fixed parameters such a theory can always be experimentally verified, and the proposed variants are most likely to be checked experimentally in the next few years. On the other hand, if a check with the accuracy available today gives a negative result, one can still keep the theory and readjust the parameters.

Other theories supposed to be more advanced than conventional quantum mechanics include

— the quantum mechanics of David Bohm,

— the theory of consistent quantum histories,

— the many-worlds interpretation of quantum mechanics.

In *Bohm's quantum mechanics*, the wave function of the particle is supplemented with its path. By assumption, the motion of the particle may be regarded as a motion along a path, but the statistics of paths is derived from the Schrödinger equation. Thus, the predictions of the theory coincide with the predictions of conventional quantum mechanics. In a sense, Bohm's theory differs from the probabilistic formulation of quantum mechanics mostly terminologically, but such distinctions are often important in various 'interpretations' and generalizations of quantum mechanics.

The theory of *consistent histories* [47–49] is based on the picture of evolution of a quantum system resembling Feynman's path integral. According to Feynman, the amplitude of propagation is represented as the sum (integral) of amplitudes corresponding to different paths leading from the starting point to the end point. In the theory of consistent histories, the total amplitude is represented as a sum of amplitudes corresponding to different 'quantum histories'. Each history (simplifying a little) can be represented as a bunch of Feynman paths. Then the question is what are the conditions under which this bunch of paths (quantum history) can be correctly associated not only with the amplitude of probability, but with the probability itself. It turns out that this can be done when the bunch of paths is broad enough. In other words, the condition can be formulated for consistent introduction of probabilities. Such sufficiently broad bunches of paths (histories) may be considered as describing classical motion.

The theory of consistent histories therefore shows how the classical evolution emerges from the purely quantum description of the system. In this case the quantum system is assumed to be closed. If we use this theory for describing the measurement, then the treatment includes both the measured system and the measuring device. The theory of consistent histories allows the necessary condition of appearance of classical features to be formulated: it is the condition of consistency of histories (in Ref. [50] this condition is proved to be not sufficient). This theory, however, is also confined to the listing of alternative classical options of evolution along with the associated probabilities. Such a theory does not describe the mechanism of selection of one of the available alternatives. So the problem formulated at the end of Section 4.1 is not solved in the theory of consistent histories.

The most radical advancement of the theory is the *many-worlds interpretation* of quantum mechanics, proposed by Everett and developed by Wheeler [51, 52], and sometimes referred to as the Everett–Wheeler interpretation. This approach considers the closed system that includes the measured subsystem, the measuring device, the observer — in short, all the Universe, the whole world. Accordingly, there is no decoherence, and there is nothing to transform the superposition of alternative pure states into a mixture. According to Everett, each component of the superposition describes the entire world, and none is privileged before the rest. There are as many worlds as alternative results of the measurement in question. Each of these worlds contains the measured system, the measuring device, the observer. The state of the system, the state of the device, the state of mind of the observer in each of these worlds correspond to one particular result of measurement, but in different worlds the results of measurement are different.

Now while in the theory of decoherence different results of measurement are possible, but only one is realized (with appropriate probability), in Everett's interpretation all possible results of measurement are real, but they are realized in different worlds. Observe that in Everett's interpretation the problem of selection of the result still exists, but in a different formulation. The question 'which of the results is realized' is not pertinent, because all results are equally real. Instead, the question is 'in which of Everett's worlds the observer finds himself'.

According to a metaphor proposed by Wheeler, at the time of quantum measurement the observer faces a kind of railway switch, and his train may choose one of several directions. Depending on the direction selected by the train, the observer will see one or other result of measurement. The possible directions of the train correspond to the alternative results of measurements, or to different Everett worlds. The train will go in one particular direction, but the rest are equally real, and the measurement yields there different results.

4.3 Quantum mechanics and consciousness

So, in the Everett–Wheeler interpretation the difficult issue about the selection of one from many alternative results of measurement is at least treated from a different standpoint. Let us try to see whether it could be possible to go further in the solution of this problem.

Let us first recall the conclusion at which we arrived earlier regarding the theory of open measured systems. The theory of open systems may be represented by the following diagram:

$$\boxed{\text{System}} \leftrightarrow$$

This diagram means that the impact of environment on the system is taken into account, although a concrete model of the environment is not included in the description. We saw that such theory

— is complete from the standpoint of physics, because it may include any part of the Universe with the possible exception of certain structures deep inside the brain in which information about the result of measurement is recorded;

— does not contain paradoxes (it leads to mixed states, not superpositions);

— can describe the selection of alternative result of measurement only phenomenologically; the mechanism of selection is left out of consideration.

The phenomenological description of selection can be formalized in the case of instantaneous (infinitesimally short) measurement by von Neumann's reduction postulate, and in the case of continuous measurement by the restricted path integral or imaginary potential [42, 43].

Such a description of selection is certainly good for all practical purposes. From the conceptual standpoint, however, the phenomenological description of selection is the weak point of the theory of open systems, which calls for the development of a more complete or more fundamental theory. Apparently this theory must be based on the treatment of closed systems, as represented by the diagram

$$\boxed{\text{System}} \leftrightarrow \boxed{\text{Environment}}$$

(the model of the environment is explicitly included in the consideration).

As we have already had a chance to see, this theory leads to superpositions of macroscopically distinct states (the paradox of Schrödinger's cat), since it does not contain the mechanism of decoherence. In addition, seeking to describe the measurement in terms of a closed system, we spread the limits of the system under consideration, so that eventually it will include observer's sense organs and those structures in his brain that are responsible for receiving information about the result of measurement.

If even one such structure is left out of what we consider the measured system, then (1) decoherence arises, which relieves us from the paradoxical superposition of distinct states, but (2) the selection of one of the alternatives is described only phenomenologically, without referring to its mechanism.

If we include in the system under consideration all degrees of freedom that could carry information about the alternatives (go over to the closed system), then there is no decoherence, and thus (1) superpositions remains, and (2) as before, nothing is said about the mechanism of selection of one of the alternatives (in this case, one component of the superposition).

Can it be then that the selection does not occur anywhere at all? This is what is assumed in Everett's interpretation: all alternatives are equally real. There is, however, one circumstance which tells us that the selection is actually made: every experimenter in a real experiment deals with just one alternative. Opening the box with Schrödinger's cat, any experimenter will see the cat either alive or dead.

Thus, trying to stay within the framework of physical conventions, we always deal with the entire set of alternatives, but when the process is described from the standpoint of consciousness of one particular observer, we only deal with one alternative. It looks like we have to make a conclusion very hard to accept for a physicist: *a theory that would describe not only the set of alternative results of measurement and the associated probability distribution, but also the mechanism of selection of one particular result, ought to include the mind (consciousness) of the observer*.

In various forms the idea of including the observer and even the mind into the theory was expressed from the early days of quantum mechanics. For example, Pauli thought that way [53]. Wigner's paper [54] contains an even stronger statement: not only the consciousness must be included into the theory, but the *mind can affect the reality*. A similar idea was expressed by Schrödinger in the conclusion to his book 'What is life?' [55]. Later we shall return to this bizarre idea of the mind affecting the reality. Here we just mention that the role of the mind in the interpretation of quantum mechanics has been much discussed lately (see, for example, Refs [7, 8 – 10, 15].

4.4 Selection of an alternative — is this the work of the consciousness?

Is there anything to add to what has already been said regarding the role of the mind in quantum measurement? We propose making one more step, seemingly small but, in our opinion, highly consequential.

As already indicated, we cannot describe the mechanism of selection of one alternative if we remain within the framework of physical conventions. This is an unsolved problem. From the arguments developed above one might conclude that the solution of this problem could be sought by including the mind of the observer in the consideration. On the other hand, although psychologists have long been studying the works of human mind, nobody has yet given a satisfactory definition of consciousness or its mechanism. The function of the consciousness remains mysterious and obscure. This also is an unsolved problem.

So we have two unsolved problems: (1) the selection of one alternative in the case of quantum measurement, and (2) the functioning of the consciousness. We know cases in the history of science when two formidable problems were solved simultaneously, as though helping to solve one another. It is quite possible that currently we are also dealing with a pair of deeply interconnected problems.

Based on this, we put forward the following hypothesis: *The function of consciousness consists in selecting one of the alternative results of quantum measurement*. In terms of Everett's many-worlds interpretation, this statement will sound somewhat different: *the function of consciousness consists in selecting one of the alternative Everett worlds* [11]. To the question 'what is consciousness†' we answer that it is the selection of alternatives in the case of quantum measurement. Only after the selection has been made do we get a definite picture of what is going on, described in the language of classical physics (for example, only after the selection does the needle of the instrument assume definite position). Before the selection, there is only the quantum pattern with its numerous alternatives. One can say that only the selection of an alternative determines what takes place in reality. But after all, this is what is understood by consciousness: it is consciousness that tells us what takes place in reality. In this way, the hypothesis that identifies consciousness with quantum selection is in agreement with our intuition.

This hypothesis is close to the ideas of Squires [7]. He believed that consciousness is like a window opening into the quantum world. It does not allow the entire quantum world to be seen, only a fragment of it (corresponding to one of the alternative results of quantum measurement or one of Everett's worlds).

Let us underline, nevertheless some distinctions of our hypothesis from what has been discussed in the literature so far. Many authors told that the explanation of quantum measurement must in one way or another involve the mind of the observer. We believe that the function of mind (consciousness) by itself is one of the stages of quantum measurement — the selection of the alternative. Accordingly, there is no need to include consciousness in the theory of measurement — it is already included. We only need to identify one of the elements of the theory of measurement (the selection of the alternative) with something known in a different theory as consciousness (the work of consciousness).

We anticipate one objection to this hypothesis. If the function of mind consists in the selection of one of the results of measurement, why then are the results selected with different probabilities, precisely those predicted by quantum mechanics? Everett's theory provides a simple and elegant answer to this question. It is demonstrated that some among the multitude of parallel worlds are identical to each other (which means that their respective subsystems are in the same

[11] If we accept this hypothesis, the work of the mind is technically described by the restricted path integral or the imaginary potential, since these are the tools for describing a continuous measurement provided that one definite result of this measurement is selected [42, 43].

† The Russian word 'osoznanie' as used by the author seems not to have a straightforward equivalent in the English language. Generally, it means 'the result of the work of the consciousness', 'conscious knowledge or recognition' 'acceptance of the validity or reality of something', 'awareness', 'understanding', 'comprehension'. We translate it as 'consciousness', or sometime, in the loose context, as mind. (*Translator's note*.)

state), and a world of a certain type occurs more frequently, the higher the quantum mechanical probability of the corresponding alternative. In other words, if N is the total number of Everett worlds, and N_i is the number of worlds corresponding to the ith alternative, then $p_i = N_i/N$ is the quantum mechanical probability of this alternative (for large N).

Thus, if the function of mind consists in the selection of one of the alternative worlds, and this selection is made at random (that is, any of the worlds is selected with equal probability), then the ith alternative result of measurement will be selected with probability p_i.

This argument strengthens our hypothesis that identifies the function of mind with the selection of the Everett world. We can now respond to the famous remark of Einstein in his dialogue with Bohr. Referring to the probabilistic interpretation of quantum mechanics, Einstein said, 'God does not play dice'. Based on our hypothesis, we may answer that *yes, God does not play dice, He equally accepts all possibilities. It is the mind of each observer that plays dice*.

Starting from our hypothesis, we note that there is just a small step to the idea of Wigner [54] that the mind can affect reality. Indeed, if usually the mind selects one of Everett's worlds at random, by chance, then why cannot we assume that there is a mind (so talented or specially trained) that can make this selection with a purpose. In this case the selection can be predetermined — or at least the probability of selecting a particular option can be increased by effort of the will†. In the context of Wheeler's metaphor, the observer endowed with such an 'active' mind can deliberately shift the switch and send the train along the desired track — or at least increase the probability of the train taking the desired track.

This of course is not a proof but pure speculation, although the conclusion seems to follow naturally from arguments developed above. At the same time, it is not easy to agree with these conclusions. Let us try to refute two possible objections. At first glance it seems that the hypothesis of the effect of consciousness on the selection of an alternative (let us call it the hypothesis of the active mind) leads to (1) inconsistency between observations of different observers, and (2) possible violation of the laws of nature. However, this is not so, or not quite so.

As it may seem, if the outcome of measurement to some extent depends on the observer, then two different observers of one and the same measurement may see different results. For example, the leader of an experimental group and his assistant will look at the instrument and see different readings because the leader wants them to be high, and the assistant wants them to be low (they probably stick to different theories, and each wants his theory to win). Of course, this is never observed in practice, which casts a shadow over the theory of active mind. More careful analysis shows, however, that the hypothesis of active mind does not imply any such inconsistency.

Let us turn to our model (3). Here the state of the leader (his mind) and the state of assistant are described by different factors (or groups of factors) in each term. Assume that they are factors α and β. It is obvious that these factors are either in the state $|\alpha_1\rangle|\beta_1\rangle$, or in the state $|\alpha_2\rangle|\beta_2\rangle$. The readings of the device seen by both colleagues are always in agreement with each other. If one observer uses the power of his will to increase the probability of getting into a certain Everett world, in the same world he will find all other people which have access to information about the reading (or its implications).

In this example, assuming that both the leader and the assistant have active minds, the leader will most likely see the high reading (and will show this to his assistant, who will have to agree); conversely, the assistant will see a low reading and will demonstrate this to his boss. The leader and the assistant will shift the switch to different tracks, and each in his mind's eye will see different Everett's worlds, but each of these worlds will be internally consistent. Of course, this arbitrariness with operation of the switch shakes one's faith in the objectivity of science — and we shall discuss this shortly.

The second possible objection is the following. At first glance it seems that if one can exercise one's will to get into a preferred Everett's world, then this feat will also change the probabilities of different outcomes of measurement — that is, the predictions of quantum mechanics are wrong, and the laws of nature do not work. The first answer is that you can only get into such an Everett's world that already exists and can always be reached in the ordinary way, when the consciousness selects one of the worlds at random. Accordingly, if a certain person has the ability to select a certain outcome of measurement at his discretion, this can always be attributed to chance: such a likelihood always exists, however small. On the other hand, such a person will be able to perform his feats over and over again. Each time his success can be explained by mere chance, but if this happens too often, the probability of chance occurrence may become quite small. Nevertheless, it will be impossible to prove with certainty that this is not a mere coincidence.

Moreover, the appearance that some person can repeatedly produce an unlikely event (work a miracle) only occurs in the mind of the miracle-worker himself (owing to the fact that his mind can purposefully select an Everett's world). And it is only in his mind that other observers are witnesses of his repeated success, and become convinced in his talent. If we try to see how the same event looks in the eyes of another observer with an ordinary mind, we find that in most cases he will see that the event promised by the miracle-worker does not come true. After all, his mind selects an Everett world at random, and will most likely end up in such a world where such an unlikely event does not happen. The conclusion is that the laws of nature can be violated in the individual experience of some people (endowed with an active mind), but people with ordinary minds, using the techniques of statistics, will not confirm this.

Let us look at this situation from a somewhat different standpoint. Assume that the man who is able to increase or decrease at will the probability of getting into some Everett world or other is an experimental scientist (like in the above example). If this is possible, then the objectivity of scientific research is at stake. How can a result be objective if the scientist can affect it, and get eventually whatever he wants? The answer to this catch is already contained in our previous argument, but we shall repeat it in a slightly different formulation. If our observer has an active mind, then he is a kind of miracle-worker, and his results may run counter to the predictions of quantum mechanics. As already indicated, however, the miracle (that is, the realization of the desired result) only occurs in his own mind. Even he himself can attribute this miracle to a fluke, because the result is admitted

† This hypothesis is correct is the number of Everett'e worlds N is infinite. (*Author's note to the English edition.*)

by quantum mechanics, even though with small probability. Finally, any other observer, who does not have an active mind and selects an Everett world at random, will as a rule end up in such a world where the result of the experiment corresponds to the most probable of the alternatives predicted by quantum mechanics (and in which the miracle-worker flunks). Personal experience of any individual with a passive mind will always confirm the conventional probabilistic quantum mechanical predictions, and all miracle-workers will be dismayed.

To make this last conclusion more clear, let us put it as follows. While the miracle-worker is working alone in his laboratory, with a high probability he gets the desired result, while the probability of the result which is most likely from the standpoint of quantum mechanics is low. Eventually the result is published and becomes available for many readers. Consider any of these readers who does not have an active mind (or even has an active mind but is not keen on obtaining any particular result of this experiment). What is the result that he finds in the publication? The answer is obvious. His mind will occur in one or other Everett world in accordance with the conventional quantum mechanical distribution of probabilities. Accordingly, in the publication this person will most likely see the result that is most probable according to quantum mechanics. So even if the miracle-worker favored the result associated with a low quantum mechanical probability, the audience of the journal, made up of ordinary people, will find in the publication the result that is most probable.

The final conclusion may be formulated as follows. Even if we accept the hypothesis of active mind, the objectivity of scientific results is guaranteed by the fact that each finding is published and used by a large number of scientists that have no active mind and no opportunity to affect the selection of quantum mechanical alternative. This makes the hypothesis of active mind acceptable. It does not lead to absurd conclusions. Of course, this is not a proof either, and it remains unclear whether this hypothesis is true or not. Quite possibly it can be neither proved nor refuted, and so anyone may believe in it or not. In either case there will be no contradiction with what is actually observed.

This resembles a rather common opinion that the existence of God is purely a matter of faith. In the consciousness of a true believer, in his personal experience there may be a proof of God's existence that is quite conclusive. But it cannot be either proved or disproved by the methods of science.

4.5 Quantum world and classical world

If we take the standpoint developed in the previous section, then the relationship between the quantum world and the classical world looks much different. The usual interpretation of the relationship between these worlds is illustrated with the following diagram:

$$\boxed{\text{Quantum vector of state}}$$
$$\downarrow$$
$$\boxed{\text{Classical reality}}$$

The classical world is something we observe, and therefore interpret it as real. The quantum world (the vector of state or wave function) only exists as a mathematical abstraction that can predict classical reality, and then only in terms of probabilities. In any case, it is difficult to treat the quantum world defined in this way as an objective reality.

If we accept Everett's interpretation, supplemented with the hypothesis that the selection of one of the parallel Everett worlds is a function of consciousness, then we get a quite different relationship between the quantum and classical worlds:

$$\boxed{\text{Objective quantum world}}$$
$$\downarrow$$
$$\boxed{\text{Illusion of classical reality}}$$

In this scheme the quantum world is objective because it does not depend on the consciousness of the observer. It exists in the form of parallel worlds, each of which is no less real than the rest. As regards the classical world, it comes into existence only after the consciousness has selected one of the parallel worlds. Other worlds do not cease to exist — therefore, the reality of the selected world is just an illusion occurring in the mind of the observer.

This relationship can be illustrated by a drawing in which the quantum world is represented as a complex geometric body, whereas 'classical reality' is just a projection of this body. The work of consciousness consists in the selection of one of the possible projections, but in no event does this projection reflect the entire complexity of the objectively existing quantum world.

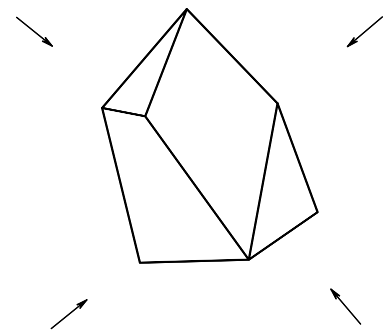

Figure. Classical reality arises in the mind as the selection of one of the alternative results of measurement, and is a picture of the quantum world from one of the possible viewpoints. In the quantum world all alternatives objectively exist.

5. Conclusions

In this paper we have considered the problem of quantum measurements, and our treatment falls into two parts quite different in nature. Most of the article (Sections 1 – 3) is devoted to the analysis of specific features of the entangled states of quantum mechanical systems and the picture of decoherence based on these states and associated with quantum measurements. We showed that the entangled states not only explain what goes on in the case of quantum measurement, but also give rise to new applications of quantum mechanics, known generically as quantum information.

In the last Section 4 we discussed the 'tiny cloud' that still remains in the theory of quantum measurements based on decoherence. This 'cloud' — an unsolved conceptual problem — stems from the fact that the theory of decoherence, while correctly describing the alternative results associated with quantum measurement and the distribution of probabilities with respect to these alternatives, does not say anything about the process of selection of one of the alternatives.

Our analysis reveals that this problem lies essentially outside of physics, and therefore can safely be disregarded. At least, this attitude is taken by most physicists; it is quite legitimate and does not lead to any inconsistencies or contradictions in purely physical problems. Keeping to this standpoint, one can successfully solve all practical problems. Accordingly, one may maintain that the theory of decoherence and the related theory of open measured systems are quite complete and do not call for any extension except for purely technical development (which is very actively under way, see the reviews [42, 43]).

There are physicists, however, many of them noted, and Wigner among them, who are not content with this level of solution of the problem of measurement. In Section 4 we discussed the attempts to move to a more fundamental level, and characterized in brief some directions of further development of the theory that allow extending it beyond the limits of the theory of decoherence and formulating it in terms of closed systems rather than open.

In our opinion, the most interesting and consistent among these extended theories is the many-world interpretation of quantum mechanics of Everett–Wheeler. To this interpretation we added the hypothesis that the selection of a particular Everett world is something that is called the work of consciousness. This small but fundamental step leads to a very beautiful theoretical construction, and may form an entirely new basis for the theory of consciousness.

If we use all the arguments developed above to try to see the future, we could assume that

— the practical applications of entangled states will continue to develop;

— quantum mechanical experiments will involve consciousness and the work of mind,

— the quantum theory of measurements may eventually lead to a theory of consciousness as a fundamental physical property only found in living matter.

The last statement remains to a large extent speculative, but still calls for special attention, because its successful development may radically extend the subject of physics, raising the science to a fundamentally new level.

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