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Concept of consciousness in the context of quantum mechanics

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Abstract. Conceptual problems of the quantum theory of measurement are considered, which are embodied in well-known paradoxes and in Bell's inequalities. Arguments are advanced in favor of the viewpoint that these problems may hardly be solved without direct inclusion of the observer's consciousness in the theoretical description of a quantum measurement. Discussed in this connection is the so-called many-worlds interpretation of quantum mechanics proposed by Everett, as is the extension of Everett's concept, which consists in the assumption that separating the quantum state components corresponding to alternative measurements is not only associated with the observer's consciousness but is completely identified with it. This approach is shown to open up qualitatively new avenues for the unification of physics and psychology and, more broadly, of the sciences and the humanities. This may lead to an extension of the theory of consciousness and shed light on significant and previously misunderstood phenomena in the sphere of consciousness.

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From the Editor

Under Soviet power, only dialectical materialism was regarded as a scientific philosophy. That is why, under the conditions of censorship, it was actually impossible to publish papers that stated or supported views different from those declared by Marxist philosophers. Meanwhile, in democratic countries such views were, and are, widely discussed. As far as physics is concerned, the aforementioned especially applies to the discussion of methodological issues related to quantum mechanics. In contemporary Russia, where the freedom of speech has been proclaimed and there is no censorship, the situation has radically changed. This is the reason why the Editors of *Physics – Uspekhi.* have published M B Menskiĭ's paper [1], with an eye to bringing back the Russian physics community to the discussion of topical problems of quantum physics (it would suffice to mention the attention to quantum computers). Later on, there followed a number of letters on this subject [2], which were not even refereed, to provide an opportunity to reflect different views on quantum mechanics, including the views with which many members of the Editorial Board (I, in particular) strongly disagree. After that, several other articles were published on the same subject [3, 4] and under the same conditions. Finally, published below is a new lengthy paper by Menskiĭ concerned with the interpretation of quantum mechanics, the emphasis being placed on the possible, in the author's opinion (and not only in his), relation between the quantum theory of measurement and the observer's consciousness. I will make remarks to the point below. Here, I only emphasize that Menskiĭ's paper is now published largely as an exception. The point is that *Physics – Uspekhi* is a journal intended to cover progress in branches of physics and related scientific avenues. Of course, this policy cannot be strictly followed; sometimes

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¶ 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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we also publish methodical notes and other materials. But we cannot and will not often give the floor for discussion of philosophical problems and, in particular, of the relation between quantum theory and epistemology, psychology, etc. By the way, Menskiĭ himself elaborates on this subject elsewhere [5].

I now allow myself, as mentioned above, a remark concerning the essence of the issues discussed by Menskiĭ. As is well known, idealism and, in particular, solipsism cannot be refuted by purely logical reasoning; to decide between the materialistic and idealistic viewpoints requires invoking intuitive judgement (discretion) [6]. As far as I can judge, Wigner's standpoint, about which Menskiĭ writes early in his paper, is solipsism, idealism. Materialists, among whom I belong, rely on a different intuitive judgement. To be specific, I do not understand why the so-called reduction of a wave function is somehow related to the observer's consciousness. For instance, in the famous diffraction experiment, an electron passes through slits and then a 'spot' appears on the screen (photographic plate), and it thus becomes known where the electron ended up. The emergence of the 'spot' is, evidently, the result of interaction between the incident electron and the photographic plate material. The principal feature of quantum mechanics is that, generally speaking, it predicts only the probability of events. Specifically, in the diffraction experiment, quantum mechanics predicts the distribution of the 'spots' over the screen or the probability of the electron arriving (i.e., a 'spot' appearing) at an arbitrary point on the screen. This situation is the reflection of the wave – corpuscle dualism, i.e., of the fact that the electron (or, of course, any other microparticle) is not a 'material point' of classical physics, which moves along some definite path. When the state of the electron after its interaction with atoms in the photographic plate is described with the aid of a wave function, this function is evidently different from the initial one and, say, is localized at a 'point' on the screen. This is just what is commonly referred to as the reduction of a wave function. Naturally, the observer will also see the 'points' on the screen the next day after the performance of the experiment, and I do not understand why his consciousness is to play some special role in this case. Such an interpretation of quantum mechanics as indicating the probabilities of the observed events is, to interpret it simplistically, its 'ordinary' or, as they sometimes say, the Copenhagen interpretation (see, e.g., Refs [7 – 9]). Anyhow, this is precisely how I understand the situation. However, there exist different opinions, and the issue of measurement in quantum mechanics is not elementary and is under debate, as is already clear from Menskiĭ's paper. Menskiĭ and several other undoubtedly well-qualified physicists adhere to a viewpoint different from the 'ordinary' one, which is reflected in this paper. As far as I understand, this is not merely solipsism, which I perceive in Wigner's reasoning, but something more complicated. Furthermore, it is a matter of common knowledge that the origin of life and consciousness has not been elucidated, the problem has not been solved (see, e.g., Ref. [10]). It would therefore be a mistake to simply wave away the discussion of the origin of human consciousness and some relation between this problem and quantum mechanics. Under the circumstances, the publication of Menskiĭ's paper appears to be justified and it will conceivably provoke interest. This is precisely what is required, because progress in the area of interpretation of quantum theory of measurement is impossible without further analysis. It may turn out that everything is perfectly clear and, say, the 'ordinary' interpretation will finally triumph. Such a conclusion would also be a success. Naturally, should sufficiently convincing new results be obtained in the area under discussion, they will also be covered by *Physics – Uspekhi*.

V L Ginzburg

References

1. Menskiĭ M B *Usp. Fiz. Nauk* **170** 631 (2000) [*Phys. Usp.* **43** 585 (2000)]
2. Menskiĭ M B *Usp. Fiz. Nauk* **171** 459 (2001) [*Phys. Usp.* **44** 438 (2001)]
3. Belinskiĭ A V *Usp. Fiz. Nauk* **173** 905 (2003) [*Phys. Usp.* **46** 877 (2003)]
4. Popov M A *Usp. Fiz. Nauk* **173** 1382 (2003) [*Phys. Usp.* **46** 1307 (2003)]
5. Menskiĭ M B *Voprosy Filosofii* (6) 64 (2004)
6. Feĭnberg E L *Dve Kul'tury. Intuitsiya i Logika v Iskusstve i Kul'ture* (Two Cultures. Intuition and Logic in Art and Culture) 3rd ed. (Fryazino: Vek-2, 2004) [Expanded German edition: *Zwei Kulturen. Intuition und Logik in Kunst und Wissenschaft* (Berlin: Springer-Verlag, 1998)]
7. Landau L D, Lifshitz E M *Kvantovaya Mekhanika. Nerelyativistskaya Teoriya* (Quantum Mechanics: Non-Relativistic Theory) (Moscow: Nauka, 1989) [Translated into English (Oxford: Pergamon Press, 1977)]
8. Kadomtsev B B *Usp. Fiz. Nauk* **173** 1221 (2003) [*Phys. Usp.* **46** 1183 (2003)]; *Dinamika i Informatsiya* (Dynamics and Information) (Moscow: Red. Zh. 'UFN', 1999)
9. Bohr A, Mottelson B R, Ulfbeck O *Phys. Today* **57** (10) 15 (2004)
10. Ginzburg V L *O Nauke, o Sebe i o Drugikh* (About Science, Myself, and Others) 3rd ed. (Moscow: Fizmatlit, 2003) p. 56 [Translated into English (Bristol: IOP Publ., 2005)]

> "In their beds at night, children ask for details about a fairy tale. How big was the pumpkin? What color were Puss-in-Boots' boots? In the same way, our reason questions our positive understanding. Now then, all that physics! Does it really disclose nothing but rules and recipes?"
> Bernard d'Espagnat *In Search of Reality* [1]

1. Introduction

In 2000, the Editors of *Physics – Uspekhi* initiated a discussion of the methodology of quantum physics and, in particular, on the conceptual problems of quantum mechanics [2]. As would probably be expected, the discussion centered primarily on conceptual problems and, in particular, on the issue relating to the part that the observer's consciousness plays in quantum mechanics. In our paper, we discuss at length this 'eternal' problem of quantum mechanics, which is unique in its complexity and goes beyond the province of physics in essence.

If we restrict ourselves to a very brief formulation, the immanent feature of quantum mechanics (more precisely, of quantum physics, including relativistic physics) that distinguishes it from all remaining physics is that attempts to represent the measurement process in it as completely objective, as absolutely independent of the observer who perceives the result of the measurement have not met with success. To simplify matters still further, we say that the description of quantum measurements (at least if this is to be logically complete, consistent) must involve not only the system under measurement and the instrument but also the observer or, to be more precise, the observer's consciousness, in which the result of the measurement is fixed. This feature of quantum mechanics contradicts our intuition and inevitably leads to misunderstanding upon first acquaintance. The complex of questions emerging in this connection is most frequently grouped under the conventional name 'measurement problem'. The several decades that have passed since the advent of quantum mechanics have shown that attempts to satisfactorily solve this problem or dismiss it as nonscientific have been unsuccessful.

In the literature in this country, the measurement problem is hardly discussed, but in the 1950s it raised heated and emotional debate. By contrast, the discussion of this issue in the foreign physics literature has livened up and become broader. Foreign physicists no longer regard this problem in general as being odious, which was believed by many of them as recently as twenty years ago.

The purpose of the discussion undertaken by *Physics–Uspekhi* was, in particular, to elucidate the formulation of the 'measurement problem' and discuss possible ways to solve it. In the course of the discussion, it became clear that some physicists are even lacking a clear understanding of the essence of this problem. This is partly attributable to the fact that the conceptual problems of quantum mechanics do not play a role of any significance in practical work on the calculation of quantum systems and are therefore uninteresting to physicists oriented to practical problems. This underlies the standpoint shared by many that the 'measurement problem' is far-fetched and scholastic, although the fact that this problem has been investigated by outstanding physicists can hardly permit disregarding it so easily.

In any event, the lack of understanding of the heart of the matter by physicists significantly lowered the level of the discussion (it is not improbable that this level also sank because the first comments were intentionally published without any selection). But at the same time, this incomprehension was an indication that the statement of the problem was timely. It was evidently not to be expected that the discussion of so intricate a problem would prove to be efficient immediately after an interruption of many years that had occurred for various reasons in the literature of this country. The impetus that was nevertheless lent by this discussion would hopefully bear fruit at a later time.

We now turn to more specific issues and, after characterizing the heart of the issue as briefly as possible, discuss the present state of the 'measurement problem' and the changes in the approach to its solution seen by the last decades.

In the first half of the paper, we explain why the procedure of state reduction (collapse of the wave function), involved in the universally accepted description of a quantum measurement, is in essence a departure from quantum mechanics. Justifying this procedure calls for appealing to something that lies outside quantum mechanics. Instead, it is possible to invoke the concept of 'observer's consciousness' by introducing it explicitly into the description of measurement. This is done in Everett's interpretation (many-worlds interpretation) [3, 4].

In the second half of the paper, we enlarge on this interpretation, which seems to hold the greatest promise for the solution of the 'measurement problem'. In outlining Everett's interpretation and its implications, we rely on the hypothesis about identification of the 'observer's consciousness' with the separation of the quantum world into classical alternatives corresponding to alternative results of measurements [2]. The special role of the 'observer's consciousness' underlies the many-worlds interpretation. Nevertheless, the complete identification of the consciousness with what takes place in the measurement leads to a radical change of the viewpoint on the problem as a whole and especially on the phenomenon of consciousness. As a result, there emerges a direct relation between physics and psychology and, from a more general standpoint, between the realms of human cognition represented by the sciences and the humanities (see Section 11 as well as Ref. [5]).

2. Quantum paradoxes and the observer's consciousness

One feature of a quantum measurement is that a quantum system cannot be measured (i.e., any information about it gained) without perturbing its state, and the more information is extracted in the measurement, the stronger the perturbation. This, of course, is well known and is quantitatively treated typically using the uncertainty relation (although, in this case, too, some measurement-related subtleties are ordinarily neglected, see Ref. [6, Ch. 3] about this).

It is also known that even with the exact knowledge of the state of a system it is possible to predict the measurement result with certainty only in exceptional cases (when the system prior to the measurement is in one of the eigenstates of the observable being measured). Generally, it is only possible to calculate the probability distribution over different measurement data. This is quite sufficient for practical purposes. All (probabilistic) predictions based on suchlike calculations are amply borne out, and quantum system measurements present no problems in this sense. This 'trouble-free' approach is theoretically formulated in terms of a quantum ensemble — a set of similar systems residing in the same state. Knowing the probability of one measurement result or another, we know what fraction of the systems that make up the ensemble yield a given result in the measurement. In the general case, we are not allowed to know more; the quantum-mechanical predictions of measurement data (or of observations) are no more than probabilistic in nature.

By adopting this ideology, one can quite successfully work in quantum mechanics and never encounter the notorious 'measurement problem'. The problem is indeed extraordinary, if for no other reason than the fact that its most clear formulations have the form of paradoxes, the famous quantum-mechanical paradoxes, for instance, the paradox of Schrödinger's cat or the paradox of Wigner's friend. And physicists of a practical mind are not interested in paradoxes as long as the problems they have to solve are well-posed.

We nevertheless recall these paradoxes, on which such outstanding physicists as the authors of the above-mentioned paradoxes Schrödinger and Wigner, as well as Einstein, Bohr, Heisenberg, Pauli, Wheeler, De Witt, and many others considered it necessary to spend their time and energy.

The paradox of Schrödinger's cat is rather well known. The cat is in a closed box and beside it in the same box is an atom of a radioactive isotope, a counter of decay products, and a device that breaks an ampoule with a poison upon actuation of the counter. For as long as the atom persists, the cat is safe and sound, but when the atom decays and the counter is actuated, the cat dies of poison. Next there comes into effect the probabilistic nature of quantum mechanics: it is unknown when the atom is to decay: at every given time instant, there is only a certain decay probability. To be more precise, — at every time instant, the atom is in a superposition (linear combination) of two states: the state in which it has not yet decayed and the decayed state.

This brings up the paradox. When approaching the closed box, according to quantum-mechanical laws, we must believe that the system (atom + cat) is in a superposition of two states: (undecayed atom + live cat) and (decayed atom + dead cat). However, on opening the box we, of course, never observe any superposition whatsoever but see either a live cat (and the undecayed atom) or a dead cat (and the already decayed atom). The description of the system depends on whether we have already opened the box. In more general terms, the after-measurement system description depends on whether the observer has apprehended the result of the measurement (in the case of the Schrödinger cat, the entire procedure outlined above can be treated as the measurement and that which the observer sees on opening the box as the measurement result).[1]

The paradoxicality of what takes place in a quantum measurement is further emphasized in the paradox of Wigner's friend. Wigner [7] considered a situation in which not he himself but his friend performs measurements of some quantum system to let him know the measurement result afterwards. The result eventually reduces to the fact that the system is in one of two states: $|\psi_1\rangle$ or $|\psi_2\rangle$. The experimenter learns about the state of the system from whether he sees a light flash in the corresponding measuring device.

As in the paradox with the Schrödinger cat, in this case, too, prior to the measurement the system is in a state that is a superposition of the states $|\psi_1\rangle$ and $|\psi_2\rangle$. But how should we describe the state in which the system resides after the measurement? It turns out that this once again depends on the observer's consciousness. If the experimenter has not yet looked at the device, he describes the state as the superposition of $|\psi_1\rangle$ and $|\psi_2\rangle$. If he has, then either as $|\psi_1\rangle$ or as $|\psi_2\rangle$ (depending on precisely what he has seen). The description of the system state depends on whether the experimenter has become aware of the system state.

We have already seen this in the paradox of Schrödinger's cat. But Wigner introduces a new element because his experimenter-friend conveys to him, Wigner, the information about the measurement. For as long as Wigner does not possess this information, he describes the system state as a superposition of $|\psi_1\rangle$ and $|\psi_2\rangle$. On receiving the information, he describes it differently: either as $|\psi_1\rangle$ or as $|\psi_2\rangle$ (depending on the contents of the information transmitted). Therefore, the description of the state of Wigner's system depends on whether his consciousness has perceived the information about the measurement result that his experimenter-friend has transferred to him.

The paradoxicality of the situation is underscored by the following reasoning. Wigner says, "However, if after having completed the whole experiment I ask my friend, 'What did you feel about the flash before I asked you?' he will answer, 'I told you already, I did [did not] see a flash,' as the case may be. In other words, the question whether he did or did not see the flash was already decided in his mind, before I asked him." To realize clearly what is odd about this, we translate it into the language of formulas.

Let the prior-to-measurement state of the system under measurement be

$$|\psi\rangle = c_1|\psi_1\rangle + c_2|\psi_2\rangle\,,$$

and the state of the device be $|\Phi_0\rangle$. Then, the state of the compound system (comprising the system to be measured and the device) prior to the measurement is given by the state vector (wave function)

$$|\psi\rangle|\Phi_0\rangle = (c_1|\psi_1\rangle + c_2|\psi_2\rangle)|\Phi_0\rangle\,.$$

Let $|\Phi_1\rangle$ denote the state of the measuring device in which a flash occurs and $|\Phi_2\rangle$ denote its state in which no flash occurs. Then, the measurement result perceived by the observer is described by either the vector $|\psi_1\rangle|\Phi_1\rangle$ (if he sees the flash) or $|\psi_2\rangle|\Phi_2\rangle$ (if he does not see it). The former signifies that the device has transited from the $|\Phi_0\rangle$ state to the $|\Phi_1\rangle$ state, while the system under measurement has found itself in the $|\psi_1\rangle$ state. The latter is interpreted in a similar manner. The states of a compound system (comprising two subsystems) like $|\psi_i\rangle|\Phi_i\rangle$ are said to be factored. In this case, each of the subsystems is in a definite (pure) state, i.e., is characterized by a state vector (wave function).

We can assume, however, that the measuring device has already been actuated but the observer has not yet looked at the device. Then, the state of the complete system (including the system under measurement and the device) is obtained from the initial state

$$(c_1|\psi_1\rangle + c_2|\psi_2\rangle)|\Phi_0\rangle = c_1|\psi_1\rangle|\Phi_0\rangle + c_2|\psi_2\rangle|\Phi_0\rangle$$

by the action of the linear evolution operator or the solution of the linear Schrödinger equation. This necessarily, simply due to the linearity of this operation, yields

$$c_1|\psi_1\rangle|\Phi_1\rangle + c_2|\psi_2\rangle|\Phi_2\rangle\,.$$

Insofar as the observer has not become aware of the measurement result, he is guided exclusively by quantum-mechanical laws and should therefore describe the state of the complete system by the vector

$$|\Psi\rangle = c_1|\psi_1\rangle|\Phi_1\rangle + c_2|\psi_2\rangle|\Phi_2\rangle\,.$$

Once he has realized the measurement result, he describes the state by one of the vectors

$$|\Psi_1\rangle = |\psi_1\rangle|\Phi_1\rangle \quad \text{or} \quad |\Psi_2\rangle = |\psi_2\rangle|\Phi_2\rangle\,,$$

depending on precisely which result he observes. Wigner describes the state by the $|\Psi\rangle$ vector insofar as his friend has not let him know the measurement result, but after the announcement, by one of the vectors $|\Psi_1\rangle$, $|\Psi_2\rangle$. Once Wigner's friend (the experimenter) answers the question "What did you feel about the flash before I asked you?," Wigner should draw the following conclusion: even prior to receiving the message but knowing that the measurement has taken place and his friend knows the measurement result, he has to describe the state by one of the vectors $|\Psi_1\rangle$, $|\Psi_2\rangle$ (not knowing by which of the two, though). In this case, Wigner's description of the state is determined by his knowledge of the fact that his experimenter-friend has looked at the device, i.e., the consciousness of his friend has perceived the information about the measurement result.

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[1] The paradox cannot be explained merely by the fact that the observer is lacking information. We discuss this in Section 4.

Yet another subtlety emerges when we consider the situation where there is no live observer (Wigner's friend) of the device. In this case, simply by the linearity of quantum-mechanical equations, Wigner (like any other physicist in his shoes) must describe the after-measurement state by the vector

$$|\Psi\rangle = c_1|\Psi_1\rangle + c_2|\Psi_2\rangle\,.$$

If the 'measuring instrument' is microscopic, for instance an atom, additional experiments may allow verifying (from the presence of interference effects) that the correct state description is indeed provided by the vector $|\Psi\rangle$ rather than $|\Psi_1\rangle$ or $|\Psi_2\rangle$. In the case of a macroscopic device, there is no way of carrying out such a verification, but the vector $|\Psi\rangle = c_1|\Psi_1\rangle + c_2|\Psi_2\rangle$ may be derived theoretically, relying exclusively on the linearity of quantum-mechanical equations (for instance, the Schrödinger equation).

All this led Wigner to conclude [7] that a live observer plays a special part in quantum mechanics, somehow breaking the linear nature of evolution. When the information about the measurement result enters the observer's consciousness, the state description becomes such that it cannot result from the evolution described by a linear operator.

Wigner's paper was written a long time ago, back in 1961, and at first sight its arguments seem to be naive. But in reality, they reveal deep and truly specific features of quantum measurements, which are fully comprehended from a purely formal, mathematical aspect but do not get along well with our intuition. The conclusion from the above that is most significant for the subsequent discussion is that the observer's consciousness should be explicitly taken into consideration in the analysis of a quantum measurement. This can also be substantiated in other ways.

3. Phenomenon of decoherence

A measurement may be formally represented with the aid of a reduction procedure. In particular, in the simple example given in the previous section, the initial state $|\psi\rangle = c_1|\psi_1\rangle + c_2|\psi_2\rangle$ experiences reduction during measurement; as a result, it passes into the state $|\psi_1\rangle$ with the probability $|c_1|^2$ and into the state $|\psi_2\rangle$ with the probability $|c_2|^2$.[2] The state reduction (in combination with similar procedures that follow from the reduction and describe more complicated measurements) provides the correct phenomenological description of a quantum measurement. The question involuntarily arises of what 'really' takes place in this case and how so strange a transformation of the state as its reduction occurs. A partial answer to this question is provided by the phenomenon of decoherence [9–13, 6], which we briefly characterize by taking advantage of the example in Section 2.

As we have seen in the foregoing, when we consider the measuring device as some *quantum* system and apply a conventional quantum-mechanical description to its interaction with the system under measurement, the result of the interaction between these two systems is that their initial state

$$|\Psi_0\rangle = (c_1|\psi_1\rangle + c_2|\psi_2\rangle)|\Phi_0\rangle$$

passes into the state

$$|\Psi\rangle = c_1|\psi_1\rangle|\Phi_1\rangle + c_2|\psi_2\rangle|\Phi_2\rangle\,.$$

The state of the form $|\Psi_0\rangle$ is said to be 'factored', because it is represented by the product of subsystem state vectors. The state of each of the subsystems in this case is characterized by a certain state vector. The after-measurement state $|\Psi\rangle$ belongs to the class of *entangled states* of two subsystems (in this case, the system being measured and the device). The two subsystems in an entangled state are said to be *quantum-correlated.*

An entangled state cannot be represented as a product of two state vectors pertaining to the subsystems (cannot be factored). This signifies that although the compound system comprising both subsystems is in a pure state (i.e., its state is represented by a state vector, in this case, $|\Psi\rangle$), none of the subsystems considered separately is in a specific pure state (i.e., can be represented by any state vector). Instead, each of the subsystems can be individually characterized by a *density matrix*. For the system under measurement, the density matrix is found as follows:

$$\rho = \mathrm{Tr}_\Phi\,(|\Psi\rangle\langle\Psi|) = |c_1|^2|\psi_1\rangle\langle\psi_1| + |c_2|^2|\psi_2\rangle\langle\psi_2|\,.$$

In this calculation, to the density matrix $|\Psi\rangle\langle\Psi|$ of the combined system, we have applied the operation of partial trace over the states of the system Φ (i.e., the device). Under this operation, there emerge scalar products $\langle\Phi_i|\Phi_j\rangle$ of the basis states of this system, and when the states $|\Phi_1\rangle$ and $|\Phi_2\rangle$ are orthogonal and normalized, the expression written on the right-hand side follows.

The density matrix, unlike the state vector, describes not a pure state but what is called a mixed state. The mixed state can be interpreted as the probability distribution over some set of pure states. In this instance, the density matrix signifies that the subsystem resides in the pure state $|\psi_1\rangle$ with the probability $|c_1|^2$ and in the pure state $|\psi_2\rangle$ with the probability $|c_2|^2$. It is easily seen that this corresponds to the ordinary probabilistic description of a quantum measurement, i.e., to the reduction postulate: the measurement may yield the former result with the probability $|c_1|^2$ (and then the system being measured is in the state $|\psi_1\rangle$) and the latter result with the probability $|c_2|^2$ (with the system in the state $|\psi_2\rangle$).

The transition of the pure state $|\psi\rangle$ to the mixed state ρ is termed decoherence, because it is accompanied by the loss of information about the relative phase[3] of the complex coefficients c_1 and c_2. In this instance, the decohering of the subsystem resulted from the interaction of this subsystem with another subsystem, which led to entanglement of the states (quantum correlation) of the two subsystems.

Therefore, when we want to describe, after the measurement, only the system being measured and not include the device into the description, we must use the density matrix rather than the state vector and mixed states rather than pure ones. It is significant that the density matrix is derived by conventional quantum-mechanical techniques and contains

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[2] According to von Neumann's reduction postulate [8], every (perfect) measurement is characterized by a complete system of orthogonal projectors $\{P_i\}$, and with the ith measurement result, the initial state of the system $|\psi\rangle$ passes into $P_i|\psi\rangle$.

[3] The pure state $|\psi\rangle$ can also be represented by the density matrix $\rho_0 = |\psi\rangle\langle\psi|$. If ρ_0 is expressed in terms of the vectors $|\psi_1\rangle$ and $|\psi_2\rangle$, it turns out to differ from ρ by the presence of nondiagonal terms proportional to $|\psi_1\rangle\langle\psi_2|$ and $|\psi_2\rangle\langle\psi_1|$. That is why decoherence is also defined as the disappearance of nondiagonal terms in the density matrix.

the probability distribution over different measurement results.

If we are concerned only with probabilistic predictions (and this would be quite sufficient for all practical purposes) and have no need of any deeper analysis, the density matrix and the decoherence effect it represents may be thought of as providing the complete picture of a quantum measurement. There is nothing paradoxical about this picture and no problems like the 'measurement problem' arise at this level of analysis.

But we now revert to the deeper level of analysis. We take advantage of the approach proposed by John Bell, which has come to be very popular.

4. Bell's inequalities and Aspect's experiments

It is extremely significant that the features of quantum measurements are impossible to explain (to resolve the paradoxes) by any logically simple way. For instance, one might endeavor to attribute the probabilistic nature of predictions of measurement results to the absence of complete information about the initial state. In other words, one might assume that in the measurement of a quantum system, everything proceeds just as it does in the measurement of a classical system, with the difference that we do not know the initial state of the system exactly and cannot therefore predict the measurement results precisely. However, this assumption proves to be incorrect. The fallacy in this assumption is clearly demonstrated by Bell's theorem [14, 15] and experiments like Aspect's experiment [16, 17], which rule out 'local realism'. This signifies the following.

Bell's inequalities emerge in the analysis of experiments of the Einstein – Podolsky – Rosen (EPR) type, proposed in the famous paper Ref. [18]. The most clear form of an EPR-type experiment consists in a zero-spin particle decaying into two particles with spins $1/2$, and the spin projection on some axis is measured for each of them. These measurement data are correlated in a specific manner. This is clear from the mere fact that the sum of the spin projections of all particles participating in the reaction is conserved. This sum is equal to zero prior to the decay and should therefore remain zero after the decay. The correlation is evident when measurements for two particles are made of the projections on the same axis. Then, when the projection is equal to $+1/2$ for the first particle, the projection for the second particle turns out to be $-1/2$, and vice versa. When the axes along which the spin projections are measured do not coincide, the correlation is more complicated but is inevitably present (with the sole exception of orthogonal axes, when the correlation vanishes completely).

John Bell considered the implications that would emerge if the spin projections had specific values prior to their measurements or at least the particles prior to the measurement could be characterized by some probability distribution of their spin projections on given axes. The existence of a probability distribution of this type, even prior to the measurement, is characteristic of classical physics and has come to be known as 'local realism'. Bell showed that the EPR measurement data should, under the assumption of local realism, necessarily satisfy certain inequalities, which are referred to as *Bell's inequalities*. Therefore, having carried out the measurements and checked if Bell's inequalities are satisfied, one can verify the validity of local realism. When Bell's inequalities are not satisfied, the assumption of local realism is to be rejected.

Calculating the probabilities of different measurement data according to quantum-mechanical laws leads to violation of Bell's inequalities. If absolute trust is put in quantum mechanics, these inequalities, along with the assumption of 'local realism', should be discarded at once. However, local realism appears to be so natural and is so in line with our intuition that dedicated experiments were staged to verify Bell's inequalities.

The fulfillment of these inequalities have been verified (true, with polarized photons instead of $1/2$ spin particles, but this is an equivalent situation) by different groups of experimenters. The first report was published by Aspect et al. [16, 17]. It turned out that Bell's inequalities were violated. Consequently, the assumption of an a priori existence of a distribution over spin projections (from which Bell's inequalities are derived) are experimentally refuted.

This implies that the usual (and indispensable for classical physics) notion that the properties observed in a measurement actually exist even prior to the measurement and that the measurement merely eliminates our lack of knowledge as to what specific property exists turn out to be incorrect. In quantum measurements (i.e., for sufficiently precise measurements of quantum systems), this is not the case: the properties revealed in the measurement may not have existed prior to the measurement.

To explain this, we address ourselves again to the simple formulas given above. We consider a measurement that ascertains in which of the two states, $|\psi_1\rangle$ or $|\psi_2\rangle$, the system is (to put it differently, which of the two properties, numbered 1 and 2, the system has). The measurement gives a definite answer to this question, i.e., a choice is effected between the numbers 1 and 2, and after the measurement, the system does find itself in the state ($|\psi_1\rangle$ or $|\psi_2\rangle$) corresponding to the number chosen, i.e., the property indicated by the measurement result is inherent in the system after the measurement.

But did the system have this property prior to the measurement, i.e., was it in the state $|\psi_1\rangle$ or in the state $|\psi_2\rangle$ even prior to the measurement? Not at all. In general, prior to the measurement the system was in the state $|\psi\rangle = c_1|\psi_1\rangle + c_2|\psi_2\rangle$, which is not identical to either $|\psi_1\rangle$ or $|\psi_2\rangle$. The property exhibited in the measurement had not existed prior to the measurement. The apprehension of reality customary for classical physics, which is cognized in measurements, does not take place in quantum physics. In a sense, in a quantum measurement, the reality is created and not merely cognized! In point of fact, this implies that the classical apprehension of reality is never correct whatsoever, although in some cases, in relatively rough measurements, the classical perception of reality does not entail crude errors, i.e., provides a rather good approximation.

And now we have to *clarify* the statements made just above: precise formulations are needed in the problem under discussion, and the simple formulations that we have employed contain an inaccuracy. We have said that the measurement exhibits some property and that the system indeed has this property after the measurement (although the system had not had it prior to the measurement). In terms of formulas, after the measurement that differentiates the states $|\psi_1\rangle$ and $|\psi_2\rangle$, the system does occur in one of these states. Is this indeed the case? No, undoubtedly we can make a somewhat weaker assertion: our *consciousness* tells us that the system occurs in either the state $|\psi_1\rangle$ or the state $|\psi_2\rangle$. Thus speaks our consciousness, but whether this is so in reality is a separate question.

If that which our consciousness tells us does take place, we can formulate the following: if the measurement result is perceived by the observer, this ensures that the system is in one of the states $|\psi_1\rangle$ or $|\psi_2\rangle$. However, this is impossible to prove. Only a weaker statement is proven experimentally (we draw attention to how subtle the difference is): *if the measurement result is perceived by the observer, the assumption that the system is in one of the states $|\psi_1\rangle$ or $|\psi_2\rangle$ will never lead to a contradiction with any further observations* performed by this or any other observer.

But if the observer does not look at the device, the picture is different, even after the device was actuated. Then, the state of the combined system (the system being measured + the device) is described by the vector

$$|\Psi\rangle = c_1|\psi_1\rangle|\Phi_1\rangle + c_2|\psi_2\rangle|\Phi_2\rangle\,.$$

This signifies that neither the system being measured nor the device reside in any definite (pure) state and the combined system they make up is in an entangled (quantum-correlated) state.

The chain of reasoning has now become so complicated that there is good reason to emphasize the central points. For us, the central point is the fact that *the superposition that existed prior to the measurement does not disappear by the action of the device*, at least until the observer becomes aware of the measurement result. After the measurement, the superposition $|\psi\rangle|\Phi_0\rangle = (c_1|\psi_1\rangle + c_2|\psi_2\rangle)|\Phi_0\rangle$ passes into the superposition $|\Psi\rangle = c_1|\psi_1\rangle|\Phi_1\rangle + c_2|\psi_2\rangle|\Phi_2\rangle$ and not into one of the factored states that are the components of this superposition.

This is how it should be, because the quantum-mechanical evolution law is linear; it is described by the linear evolution operator or the linear Schrödinger equation. This law does not allow the sudden disappearance of all but one term of the superposition, as is implied by the picture of reduction occurring in the measurement. The state cannot transform to $|\psi_1\rangle|\Phi_1\rangle$ or $|\psi_2\rangle|\Phi_2\rangle$.

However, we immediately recall that this is precisely the transformation involved in the ordinary, naive picture of a quantum measurement. The observer always sees either $|\psi_1\rangle|\Phi_1\rangle$ or $|\psi_2\rangle|\Phi_2\rangle$. He always sees that only one component of the superposition persists. And because this always corresponds to observations, the change whereby all but one term of the superposition vanish was introduced into quantum mechanics by von Neumann's *reduction postulate*. The corresponding transformation is referred to as the state reduction, or von Neumann's projection, or the collapse of a wave function. Beginning with the early years of quantum mechanics, it was assumed that quantum-mechanical systems may evolve in two qualitatively different ways, for as long as they are not measured they evolve linearly, and they undergo reduction in a measurement.

This postulate, adopted in the prevailing *Copenhagen interpretation* of quantum mechanics, has always worked perfectly, and continues to work just as remarkably nowadays. From the standpoint of practical needs, techniques of calculation, and predictions, there is no reason to abandon this postulate. Moreover, for practical computational needs, this postulate (and, of course, its different purely technical elaborations and generalizations) should undoubtedly be retained. But from what standpoint can it be doubted? Because it leads to correct predictions, is it not the proof of its correctness? There is no other criterion in physics.

Yes, this is so. Those who make attempts to replace the reduction postulate with something qualitatively different do not have firm footing. And still there are grounds to make these attempts. We list these grounds with the understanding, however, that they are no proof and that abandoning the reduction postulate would be justified only when the replacing theory is experimentally confirmed.

First, the search for another way that does not rely on the reduction picture is being continued in the attempts to eliminate the paradoxicality of quantum mechanics. A very promising avenue involves abandoning the reduction postulate in the framework of Everett's concept, which is discussed below. Second, the reduction postulate itself can be criticized. We briefly consider this criticism.

The reduction postulate appears to be alien to quantum mechanics and makes it eclectic. Why should a system evolve differently when it is subjected to measurement? Measurement is nothing more nor less than the interaction with some other system, conventionally termed the device, and therefore the evolution of the combined system during this interaction (i.e., during measurement) should be linear. The superposition does not disappear in the course of this evolution, and all components of the superposition that existed prior to the measurement persist after it as well.

It is significant, of course, that the measuring system is macroscopic, and hence the classical description is a good approximation for it. However, if this is merely an approximation, the exact, i.e., quantum-mechanical, description is equally applicable. After all, the measuring system consists of the same microscopic atoms, although in great number. That is why the conclusion that the superposition cannot vanish, reached in the framework of the quantum description, as well as its further implications, is not refuted by the fact that the device is macroscopic.

Apart from the macroscopic nature of the device, also of significance is the fact that instabilities may emerge in the course of measurement to effectively lead to a situation resembling reduction. However, the 'derivation' of reduction with the aid of that kind of reasoning (see, e.g., Ref. [19, Section 2.3]) also involves approximations. That is why it cannot refute the results of the analysis based only on one circumstance — the linearity of quantum mechanics, i.e., precisely the theory that was the starting point for these approximations.

Along the line of reasoning that we pursue in the subsequent discussion, the emphasis is placed on precisely the general properties of quantum mechanics. The purpose is to endeavor by analyzing these general properties (in the present instance, primarily linearity) to derive as much as possible for the understanding of the foundations of the theory and its interpretation. On this path, one has to make steps that sometimes look like fantasy. In our view, we may live in reconciliation with such steps to the extent to which they solve the originally formulated problem (overcoming the paradoxicality of quantum mechanics), as well as substantially broaden the area of application and the capabilities of the whole theory.

Before turning to the discussion of different attempts to solve the conceptual problems of quantum mechanics, we enlarge on some papers published in *Physics – Uspekhi* in the framework of the discussion on quantum mechanics.

5. Some lines of discussion in *Physics – Uspekhi*

We dwell on only three papers published in *Physics – Uspekhi* in the framework of the discussion about the conceptual problems of quantum mechanics. The choice is purely personal and is explained merely by the wish not to digress from the line of reasoning selected.

(1) A V Belinskiĭ's paper [20] contains an interesting technical remark about Bell's inequalities with the inclusion of detector errors. The author concludes that Aspect-type experiments, despite the finite detector accuracy in these experiments, reliably refute Bell's inequalities even without further improvement of the detectors, thereby experimentally bearing out the nonexistence of local realism in nature.

But the bulk of the contents of Ref. [20] is concerned with another issue. By the thoroughly analyzed specific examples of real or thought experiments with photons, Belinskiĭ illustrates the major distinction of quantum measurements that generates the 'measurement problem': the property of a system revealed in its measurement (for instance, a specific photon polarization) might not have existed prior to the measurement. This proposition of the quantum theory of measurement, which is central to the 'measurement problem', was analyzed in detail in the foregoing. However, in the examples given by Belinskiĭ, it appears in a light that is supposedly more convincing for those physicists who are used to dealing with descriptions of specific facilities rather than with formal manipulation and abstract reasoning.

For instance, Belinskiĭ considers an experiment in which single photons are detected (emitted by a source so low in intensity that the probability of simultaneous arrival of more that one photon at the detector is negligible). In this case, evidently, it is possible to count the number of detector actuations and thereby find the number of arriving photons. All this appears so evident that we do not notice when we involuntarily yield to the temptation to use the intuition borrowed from classical physics.

But Belinskiĭ puts forth questions that do not permit one to lapse into thinking thus: "It is commonly believed that photocounts, or bursts of the detector's photocurrent, correspond to the arrival of photons. But is it so? Do quanta really exist in the light field? The detector measures the number of photons in the field. But does a definite value of this quantity exist before the measurement?" And it turns out that simple experiments can prove that the answers to these questions are negative: the light field cannot be represented as an ensemble of a definite number of photons: the number of photons is not defined prior to the instant of measurement.

For instance, the photon source can be made such that one photon is recorded at times and two photons at other times. The field should seemingly consist of single photons and photon pairs. However, this is not so, which can be proved experimentally. It would be inappropriate to go into details here. The interested reader is referred to Ref. [20], where the logic of experimenters who refute the classical notion of the number of photons is traced in detail.

(2) In Ref. [21], in the historical context, M A Popov discusses the inevitability of direct consideration of the observer's consciousness in the analysis of quantum measurements. This is significant for the 'enlightenment' of readers precisely because materials of this sort are not so easy to find in the domestic literature. In this sense, Popov's paper is highly useful. Its aim was to show that in our time, the theoretical and experimental analysis of quantum measurements has reached a level where the role of the observer's consciousness can be investigated experimentally (see above, where Bell's inequalities and Aspect-type experiments were discussed).

Some readers interpreted Popov's paper as a 'propagation of philosophical idealism' (speaking in the language typical for the past but still remembered epoch of socialism). The polemically bitter title of the paper ("In defense of quantum idealism") and some formulations that the author made at the end of the paper may indeed suggest this idea. It may well be that this should have been avoided by changing the title and eliminating some garish phrases. However, as regards the heart of the matter, rather than the form, the dominant bulk of the paper is directly concerned with physics and by no means philosophy. The author substantiates the standpoint (undeniably justified) that the progress of quantum mechanics in the last two to three decades has made the inclusion of the observer's consciousness an absolute necessity when discussing conceptual problems of quantum mechanics. With some reservations, it is valid to say that the question of the role of consciousness has become amenable to experimental verification.

If Popov's paper is considered from this standpoint, the term 'quantum idealism' used in its title sounds like a striking metaphor, which points up the necessity of taking the observer's consciousness into consideration in the most direct way. The metaphor is bold and sharp yet entirely appropriate. There is no point in recalling old Soviet stereotypes and taking for the advocacy of philosophical idealism that which is merely a loose verbal formula intended to attract attention to a significant aspect of quantum mechanics — 'the measurement problem'.

(3) To analyze the operation of the observer's consciousness, A D Panov [22] invokes the notion of decoherence, which is undeniably of paramount importance in this context. Panov discusses the decoherence occurring in a material substance, which is responsible for the realization of the measurement result by the observer (e.g., in a special material structure in the brain). The endeavor to reduce everything to ordinary physical processes occurring in physical systems is quite natural for physicists and has always constituted one of the main areas of work on the problem. And the physically clear decoherence effect is undoubtedly an appropriate instrument for endeavoring to realize suchlike reduction.

Panov makes a very important observation that the entanglement of two quantum systems (in the present instance, the system being measured and the material substance in which the measurement result is reflected, or perceived) leads to the decoherence of both of them. When the density matrix of the system being measured contains, after the interaction with the device, components corresponding to all measurement results, the same statement is applied to the observer's consciousness. We elucidate this statement.

We consider the previously introduced states $|\Psi_1\rangle = |\psi_1\rangle|\Phi_1\rangle$ and $|\Psi_2\rangle = |\psi_2\rangle|\Phi_2\rangle$ of the system being measured and the device, which correspond to definite measurement results. As we have seen, in reality, the state $c_1|\Psi_1\rangle + c_2|\Psi_2\rangle$ sets in after the measurement. We now include the observer into the description. When the measurement has been effected but the observer has not yet become aware of the result (for instance, has not looked at the scale of the device), the combined state of the system being measured, the device, and the observer is given by $(c_1|\Psi_1\rangle + c_2|\Psi_2\rangle)|\chi_0\rangle$. But once the observer has realized the measurement result (for example, the photons emitted by the device arrive at his eye and his brain properly reacts to this signal), the state becomes

$$|\Omega\rangle = c_1|\Psi_1\rangle|\chi_1\rangle + c_2|\Psi_2\rangle|\chi_2\rangle\,,$$

i.e., the entanglement of the system being measured with the device and the observer occurs.

Then, the system under measurement and the device, which are considered separately from the observer, cannot be characterized by a definite state vector. Instead, the system under measurement combined with the device (but without the observer) can be characterized by the density matrix:

$$\rho_\Psi = \mathrm{Tr}_\chi\,(|\Omega\rangle\langle\Omega|) = |c_1|^2|\Psi_1\rangle\langle\Psi_1| + |c_2|^2|\Psi_2\rangle\langle\Psi_2|\,.$$

The density matrix describes not a pure state but a mixed state of the system under measurement and the device considered as a unified system. The density matrix signifies that this system is in the pure state $|\Psi_1\rangle$ with the probability $|c_1|^2$ and in the pure state $|\Psi_2\rangle$ with the probability $|c_2|^2$. In other words, decohering of the system comprising the system under measurement and the device occurred, brought about by the interaction of this system with the observer.

It is significant, however, that the observer's state also underwent decohering in this case.

Indeed, proceeding from the entangled state $|\Omega\rangle$ and trying to describe the state of only the observer himself, we can achieve this by applying the procedure of taking the partial trace again, but this time the trace should be taken over all systems except the observer himself. For the observer (considered as a physical system), we then obtain the density matrix

$$\rho_\chi = \mathrm{Tr}_\Psi\,(|\Omega\rangle\langle\Omega|) = |c_1|^2|\chi_1\rangle\langle\chi_1| + |c_2|^2|\chi_2\rangle\langle\chi_2|\,.$$

The mixed state of the observer represented by this density matrix is interpreted in an obvious way: it is in one of the pure states $|\chi_1\rangle$ and $|\chi_2\rangle$ with the probabilities $|c_1|^2$ and $|c_2|^2$. It is significant that the mixed states both of the observer and of the system under measurement and the device are characterized by the same probability distribution.

Although we have been speaking of the observer's state for simplicity, in reality we are dealing with some material carrier of the observer's consciousness (e.g., with some structure in his brain). We see that when considering this structure, we obtain the decoherence picture that perfectly corresponds to the decoherence of material systems outside the observer.

Such an analysis is undoubtedly beneficial for the understanding of what takes place. But does it solve the measurement problem? It is evident that in the description of a measurement, we cannot restrict ourselves to only the description of the observer's decoherence but endeavor to make one more step and pose the following question: what in reality occurs after the measurement? Does the observer remain in one of the pure states $|\chi_1\rangle$, $|\chi_2\rangle$ after the measurement or should we think, being guided by the form of the state vector $|\Omega\rangle$, that none of these states can disappear and they all persist as the components of the superposition $|\Omega\rangle$? If we opt for the latter, we once again encounter a paradoxical situation and the 'measurement problem': quantum mechanics compels us to believe that both states $|\chi_1\rangle$ and $|\chi_2\rangle$ continue to exist (in the superposition), while 'worldly wisdom' shows that the observer always 'perceives' only one of them.

Sometimes one encounters the opinion that the effect of decoherence eliminates the 'measurement problem'. Even with the reasoning contained in Panov's paper taken into account, we nevertheless adhere to the standpoint that decoherence, while significantly elucidating the situation with quantum measurements, does not remove all the questions. To advance further, the analysis should, in our opinion, be continued. Following this logic, we revert to the discussion of the role of consciousness in quantum measurements.

6. Measurement problems: stages of investigation

The problem that we were trying to outline in the foregoing is often referred to as the 'measurement problem'. It was posed at the dawn of quantum mechanics and reflected the aspiration of moving beyond the framework of the Copenhagen interpretation (associated primarily with Bohr's name), which perfectly solved practical problems but left some discontent from the conceptual standpoint. Attempts to solve the measurement problem were made by many outstanding physicists, including Pauli, Schrödinger, Heisenberg, and Einstein (and, of course, Bohr himself with his brilliant analysis of the special features of quantum mechanics). However, even today, this problem can by no means be considered solved.

It is not so easy to trace tendencies in the attitude of the physical community towards the 'measurement problem', because every generation of physicists begins to comprehend it to some extent anew and is able to introduce something new in its solution only after an arduous and long period of familiarization with the problem. Nevertheless, it seems to us, we can distinguish three qualitatively different stages in the investigation of this problem.

The first stage, when all the founding fathers of quantum physics addressed this subject to some extent, was noted for enthusiasm and optimism of researchers. The enthusiasm and interest were maintained by the fact that the problem ushered physicists into an entirely new, previously unknown and therefore interesting realm of metascience and philosophy, leading them to compare the existing and newly emerging specific propositions of science with the most general methodological issues and quite frequently with world outlook. The optimism, which is quite natural at the inception, was also generated because extremely potent intellectuals participated in the research.

At that period, different lines were explored. But serious advances were made only along one of them: the Copenhagen interpretation of quantum mechanics, which relied on the von Neumann reduction postulate, was formulated and polished to the state of a clear algorithm. In point of fact, this interpretation was a compromise, which made it possible to work in quantum mechanics having no doubt as to the correctness of this work. In essence, the conceptual difficulties were not overcome, but those who were not concerned with them could forget about them without the apprehension of losing orientation (as might occur in the making of quantum mechanics).

The second stage began when it became clear that the first results contributed little to the understanding of the 'measurement problem' except maybe a better understanding of the problem itself, its extraordinary nature, and its scale. This stage was characterized by a nearly universal belief in the Copenhagen interpretation and marginalization of investigations into the 'measurement problem'. The time had passed when the understanding of quantum mechanics (at the intuitive level) seemed to be, and indeed was, indispensable to efficient work. There now existed a clearly formulated system of rules, and obtaining results in the framework of this system required only the mathematical treatment of a specific problem, i.e., calculations. The issue of understanding came to seem superfluous, and the majority of physicists were no longer concerned with it. Papers on the 'measurement problem', which would nevertheless appear from time to time, changed in character and became more scholastic. Proposed instead of bold new solutions were different formulations of the old ones, which changed these old formulations in so subtle a verbal nuance that the significance of changes was clear (and interesting) to only a narrow circle of active participants in the discussion. The majority of physicists considered this discussion wholly irrelevant to physics.

In 1957, Everett [3] came up with a very bold and radically new 'many-worlds' interpretation of quantum mechanics. It marked the beginning of a new stage in the investigation into the 'measurement problem'. Everett's paper was initially noticed by few. Such famous physicists as DeWitt and Wheeler [4] were among those who became interested in this paper, which nevertheless remained unnoticed by the broad scientific community. However, it played and continues to play the leading part at the new stage of investigation.

This stage properly commenced approximately two decades ago and continues to the present day. The interest in the 'measurement problem' has remarkably quickened and the people engaged in the problem significantly grew in number. There were reasons for these changes. Quantum mechanics had essentially changed to become an engineering science, and therefore the overall number of physicists involved in it became much greater than before. Furthermore, all the preceding development of quantum mechanics had shown that it can find application in quite unexpected areas, and hence the quest for and mastering of new applications to an increasing extent called for people unconstrained by tenets. All this changed the very atmosphere of the quantum-mechanical community and significantly moderated its conservatism.

There were also more specific reasons for rekindling the interest in the conceptual problems of quantum mechanics, in the 'measurement problem'. Required were not only calculations of the ensembles of quantum systems (atoms, electrons, photons, etc.), but of individual systems as well (a single electron in single-electron devices, a single ion in a magnetic trap, etc.). The 'ensemble' ideology was no longer quite suited to describe the behavior of suchlike systems. It was necessary to be able to describe not only an ensemble of systems but also an individual system. Furthermore, for purely practical purposes (e.g., in quantum optics), the demand existed to calculate not a single measurement but a series of measurements performed over the same individual system or a measurement continuous in time. In these conditions, the statement insistently repeated in textbooks on quantum mechanics that the state vector (wave function) describes a quantum ensemble rather than an individual system came to generate increasingly more discontent. The ensemble ideology, in which there emerge no conceptual problems at all, became manifestly insufficient.

Furthermore, there appeared qualitatively new applications of quantum mechanics whose realization required a far deeper understanding of the specific character of quantum mechanics. These new applications were united under the common title quantum informatics to embrace quantum cryptography, quantum teleportation, and, above all, quantum computing. The new technologies that emerged on this basis employed precisely those specific features of quantum systems which generate the 'measurement problem'. The development of quantum-information systems in general and quantum computers in particular invited a considerably deeper understanding of the essence of quantum mechanics and its distinctions from the classical one. In addition, it was necessary to be able to correctly describe the behavior of such systems, which have quantum and classical properties simultaneously.

Of course, it is invalid to say that solving the 'measurement problem' was required before solving practical technological problems. However, developing methods for solving practical problems invited work at an extremely high level of understanding of quantum mechanics, which is close to the level of formulation of this problem. This broadened the circle of those concerned with the conceptual problems of quantum mechanics and the circle of those who worked actively in this area.

7. Everett's concept and separation of alternatives

What direction does the quest for solving the conceptual problems take? Not pretending to present complete coverage, we mention only one direction, which is supposedly the principal one. This is a return to Everett's concept (or interpretation) [3], which was proposed back in the 1950s. Everett himself called it the relative state interpretation of quantum mechanics; however, more recently, after Wheeler's and DeWitt's papers [4], it came to be known as the many-worlds interpretation. This name owes its origin to the fact that Everett's concept permits the existence of numerous (actually, an infinite number) of classical realities, which may be intuitively represented as the set of classical worlds.

The many-worlds, or Everett's, interpretation, which was earlier considered too fantastic, has been actively discussed and adopted by many scientists. Many aspects of this interpretation were thoroughly studied and different versions of its development were proposed. Vaidman [23] wrote a rather comprehensive review of the literature on this subject, which was included in the electronic Stanford Encyclopedia of Philosophy. Here, far from being a complete reflection of all viewpoints, we highlight only some minimal and yet logically complete lines of reasoning, which have, in our opinion, attractive new prospects.

We first of all explain Everett's interpretation (concept) by continuing the logic of reasoning started in the preceding sections. We adduced plausible reasoning testifying to the fact that von Neumann's reduction postulate is alien to quantum mechanics and has been adopted in it (at the cost of eclecticism) only to evade conceptual problems rapidly and easily, not solving them in essence, and go over to practical calculations. In the case of von Neumann's reduction, of the initial superposition in the previously used example $c_1|\psi_1\rangle + c_2|\psi_2\rangle$, there remains only one component (e.g., $|\psi_1\rangle$ or maybe $|\psi_2\rangle$). But at variance with this picture, the linearity of quantum mechanics requires that all terms of the superposition should persist. In the measurement, there only occurs entanglement of the system under measurement and the environment, i.e., the superposition takes the form $c_1|\psi_1\rangle|\Phi_1\rangle + c_2|\psi_2\rangle|\Phi_2\rangle$. Everett's concept may be treated as an attempt to seriously make this argument and consistently take it into consideration.

We therefore attempt to be consistent and not 'spoil' quantum mechanics by its alien reduction postulate and, conversely, rely on its immanent linearity. We are then forced to conclude that after the interaction, which we term the measurement, the state of the system and the device assumes the form $c_1|\psi_1\rangle|\Phi_1\rangle + c_2|\psi_2\rangle|\Phi_2\rangle$. None of the components of this superposition may be discarded (in general, the superposition may contain many or even an infinite number of components, depending on the type of measurement). If these superposition terms are not discarded, they all are to be interpreted. This is precisely what Everett did.

In Everett's concept (more precisely, in its equivalent many-worlds interpretation), different terms of the superposition are assumed to correspond to different classical realities, or classical worlds. These realities, or worlds, are assumed to be exactly equivalent, i.e., none of them is more real than the others. As a result, we obtain the many-worlds picture in the Everett – Wheeler – DeWitt sense.

And what is to be done with the consciousness? Because every observer sees only one measurement result, an inevitable reduction seemingly occurs in her consciousness, the choice of one superposition component out of two (or many). Is this at variance with the many-worlds concept? The apparent contradiction is solved quite easily: it is as if the observer's consciousness splits (is divided), such that in every one of the classical worlds she sees what takes place in this world. We now show this.

We let the vector $|\chi_0\rangle$ denote the initial state of the observer when she has not yet become aware of the measurement results (maybe it has not yet been completed or maybe she has not yet looked at the devices). Let $|\chi_1\rangle$ (accordingly $|\chi_2\rangle$) denote her state at the moment when she already knows that the measurement yielded result 1 (accordingly 2). Then, the system of three (the system under measurement + device + observer) prior to the measurement is in the state $(c_1|\psi_1\rangle + c_2|\psi_2\rangle)|\Phi_0\rangle|\chi_0\rangle$, after the measurement but prior to perceiving the measurement result is in the state $(c_1|\psi_1\rangle|\Phi_1\rangle + c_2|\psi_2\rangle|\Phi_2\rangle)|\chi_0\rangle$, and after perceiving it in the state $c_1|\psi_1\rangle|\Phi_1\rangle|\chi_1\rangle + c_2|\psi_2\rangle|\Phi_2\rangle|\chi_2\rangle$.

'Everett's' interpretation of this expression is evident: in every one of the classical worlds, the observer sees (realizes) that which took place in precisely this world. In the world denoted by number 1, the observer is in the state $|\chi_1\rangle$. This signifies that she has perceived the measurement yielding result 1, i.e., that the system being measured and the device are in the state $|\psi_1\rangle|\Phi_1\rangle$. Similarly, in the world number 2, the observer is in the state $|\chi_2\rangle$, i.e., in her consciousness, the picture of what is taking place corresponds to the state $|\psi_2\rangle|\Phi_2\rangle$ of the system under measurement and the device (see Fig. 1).

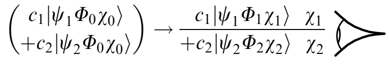

Figure 1. Separation of alternatives.

Therefore, *the observer's consciousness splits, is divided, in accordance with how the quantum world is divided into the ensemble of alternative classical worlds*. In our example, there are only two alternatives; generally, the number of alternative classical worlds turns out to be equal to the number of alternative results that the measurement may yield. We note, however, that in reality, the number of classical worlds may be arbitrarily large, even infinite, and after the measurement they split into classes (also infinite in this case) corresponding to alternative measurement results.

In the ordinary (Copenhagen) picture, a reduction of a state or, the equivalent, a selection of one alternative measurement result of all possible ones occurs. This may be termed selection of an alternative. All except the selected alternative vanish after the reduction. Going to Everett's interpretation, we see that no reduction, or selection, of a single alternative occurs. Instead, splitting, or division, of the quantum world state into alternative classical 'realities', or worlds occurs. The observer's consciousness perceives different classical worlds independently of each other. We can conventionally say that the consciousness splits into components, each of which perceives only one classical world. The observer subjectively perceives what is going on in such a way as if there exists only one classical world, specifically that which she sees around her. However, according to Everett's concept, in reality in all alternative worlds, it is as if 'replicas' of the observer exist, whose sensations provide to each of them the picture of precisely the world she 'lives' in.

In Everett's interpretation, there appears some duality, which is rather hard to comprehend. All alternatives are realized, and the observer's consciousness splits between all the alternatives. At the same time, the individual consciousness of the observer subjectively perceives what is going on in such a way as if there exists only one alternative, the one she exists in. In other words, *the consciousness as a whole splits between the alternatives but the individual consciousness subjectively chooses* (*selects*) *one alternative*.

To avoid misunderstanding, we note that in one (any) of Everett's worlds, all observers see the same thing, their observations are consistent with each other (unless, of course, we are dealing with possible purely human errors, but we assume perfect observers). This follows because, owing to the linearity of quantum-mechanical evolution, the initial state

$$(c_1|\psi_1\rangle + c_2|\psi_2\rangle)|\Phi_0\rangle|\chi_0^{(1)}\rangle|\chi_0^{(2)}\rangle$$

of the system being measured, the device, and two observers passes into the state

$$c_1|\psi_1\rangle|\Phi_1\rangle|\chi_1^{(1)}\rangle|\chi_1^{(2)}\rangle + c_2|\psi_2\rangle|\Phi_2\rangle|\chi_2^{(1)}\rangle|\chi_2^{(2)}\rangle\,.$$

The states involving the factors $|\chi_1^{(1)}\rangle|\chi_2^{(2)}\rangle$ or $|\chi_2^{(1)}\rangle|\chi_1^{(2)}\rangle$, which would imply the inconsistency of observations, can in no way appear.

This is Everett's concept in brief. At first, it seems fantastic and too complicated. But this is not exactly so.

First, Everett's concept logically follows from the single and seemingly quite natural assumption that the linearity of quantum mechanics is not violated in the course of interaction between the system under measurement and the device and the subsequent action of the device on the observer.

Second, the entire picture seems more fantastic than it actually is when they speak, endeavoring to speak with clarity, about many classical worlds. In actual fact, not only does the many-worlds picture excessively dramatize the situation, but may also mislead (and quite often does so) those who familiarize themselves with it without sufficient background in this problem. There is good reason to recall from time to time (and to necessarily do so whenever difficulties or hesitation show) that in reality, no 'many classical worlds' exist at all. There is only one world, and this is a quantum world, and it is in the superposition state. It is simply that every component of the superposition taken separately corresponds to what our consciousness perceives as the picture of the classical world, and to different superposition terms there correspond different pictures. Each classical world is just one 'classical projection' of the quantum world. These different projections are produced by the observer's consciousness, while the quantum world itself exists independently of whatever observer.

When we say 'different superposition components' in lieu of 'different classical worlds', many misunderstandings that occur in the popular literature and in discussions on this issue disappear. For instance, the many-worlds picture creates the illusion that one classical world transforms into several (or even an infinite number) of worlds at the instant of measurement. In this case, they sometimes even speak about a monstrous nonconservation of energy under this 'multiplication of worlds'. In reality, there is nothing of the kind in Everett's interpretation.[4] Prior to the measurement, as well as after it, there exists the single state vector that describes the state of the quantum world. At the instant of measurement (more precisely, at the instant of the interaction between the system being measured and the device), specific changes in this state and in its describing vector occur: the entanglement between the system being measured and the measuring device (the measuring medium). For a formal description of this change, we represent the state vector as a superposition of several components and show how each of these components changes in the measurement (in the interaction). This analysis was discussed at length in the previous sections.

Not only is the world branching oversimplified, but so is the mere idea that the measurement takes place simultaneously at all points of a finite domain (in which the wave function of the system under measurement is nonzero) at a specific time instant. In particular, this is incompatible with the special theory of relativity, in which the simultaneousness of events at different points cannot be determined at all. All these difficulties arise from the idealization contained in the notion of instantaneous measurement. They disappear in going over to the picture of continuous measurement (in this connection, see Ref. [25], where the measurement of position is discussed in the relativistic theory framework). Below, in Section 9, we discuss continuous measurement in greater detail and in this connection introduce another method of describing alternatives — with the aid of corridors of paths. With this description, the question of classical world 'multiplication' does not arise at all.

There is one truly significant objection to Everett's concept. It consists in the fact that this concept is impossible to verify, or at least it appears so at first glance. Because all formulas in it are the same as in the standard quantum mechanics, the predictions obtained in the framework of this concept are no different from those that follow from the standard quantum-mechanical calculations carried out in the framework of the Copenhagen interpretation. This is precisely the reason why Everett's concept is merely a different interpretation of quantum mechanics and not a different quantum mechanics.

Therefore, it appears at first sight that the many-worlds interpretation is impossible to confirm or refute by experiment, and in some sense this is so indeed. This is a serious drawback, because constructing a rather (conceptually) complex interpretation that is impossible to verify seems to be too high a price to be paid for making the theory more consistent in the purely logical aspect.

This is the reason why several of Everett's proponents suggested that his concept should be modified so as to make it verifiable. We believe, however, that Everett's concept can be verified even without any modification by resorting to experiments or, rather, to observations of a special kind, specifically, observations of individual consciousness. This is discussed at the end of the paper, and we now try to specify more precisely how consciousness is to be treated in the framework of Everett's concept.

8. Identification of consciousness with separation of alternatives

Two aspects of a quantum measurement — decohering and alternative choice (selection) — have different statuses in quantum mechanics. Decohering, i.e., the transformation of the pure state

$$|\psi\rangle = c_1|\psi_1\rangle + c_2|\psi_2\rangle$$

to the mixed state

$$\rho = |c_1|^2|\psi_1\rangle\langle\psi_1| + |c_2|^2|\psi_2\rangle\langle\psi_2|\,,$$

is easily derived by conventional quantum-mechanical techniques from the picture of the interaction between the system being measured and the measuring device (see Section 3). There is nothing extraordinary or incomprehensible about decohering. It is generated by the entanglement of the system being measured with the measuring device, which in turn is caused by their interaction.

Extraordinary or, as already noted, alien from the quantum-mechanical standpoint is the second aspect of a quantum measurement — the choice (selection) of one of the existing alternative measurement results. This is mathematically expressed by the transition from the density matrix ρ to one of its components $|\psi_1\rangle\langle\psi_1|$ or $|\psi_2\rangle\langle\psi_2|$, i.e., again to the pure state $|\psi_1\rangle$ or $|\psi_2\rangle$. Alternatively, the selection may be described as a transition from the pure (but entangled) state of the system under measurement and the device $|\Psi\rangle = c_1|\psi_1\rangle|\Phi_1\rangle + c_2|\psi_2\rangle|\Phi_2\rangle$ to the state described only by one component of this superposition.

The evolution laws of quantum-mechanical systems do not provide for this transition (reduction of state). No interaction may give rise to this transition. As already noted, it was artificially introduced into the quantum theory of measurement (in the form of reduction postulate) to describe what is actually observed in the measurements of quantum systems with the use of classical devices, but this description eclectically unites the quantum theory and the classical one. If we assume that the quantum theory is correct and in doing this we are consistent, it must be admitted that reduction cannot take place at all and should be excluded from the

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[4] Tegmark [24] expressed this idea in the following vivid form: "What Everett does NOT postulate: At certain magic instances, the world undergoes some sort of metaphysical 'split' into two branches that subsequently never interact."

theory. Precisely this is done in Everett's concept. However, there is a need to somehow explain why the observer always sees only one alternative.

Let us ratiocinate. If objectively (i.e., in accordance with quantum-mechanical laws) no selection of alternatives occurs and nevertheless the observer always becomes aware of a single alternative, this means that the alternative selection takes place in the observer's consciousness.

This idea is not new. Both Everett and all his followers admit in one form or another that the alternative selection is associated with consciousness (see, e.g., Refs [26–29]). But unlike other authors, we reinforce this proposition and assume [2] that it is more than merely an association between two different phenomena or notions and that these phenomena, which seem to be different (while related) phenomena, are in fact identical with each other. In other words, we assume that the selection of an alternative should be identified with the consciousness. We now specify this more precisely.

Everett's concept deals with two aspects of consciousness (see Section 7). The consciousness as a whole splits between alternatives, and a 'component' of consciousness lives within one classical alternative. In psychology, only that which is subjectively perceived is termed the consciousness, i.e., only the 'classical component' of the consciousness, according to our terminology. Therefore, to identify the notion of 'consciousness' with some notion from the quantum theory of measurement, we must broadly interpret the consciousness as something capable of embracing the entire quantum world rather than exclusively as its classical projection. Therefore, we arrive at the following *identification hypothesis*:

> The ability of a human (and of any living creature) referred to as consciousness is the same phenomenon as that which is termed the reduction of state or alternative selection in the quantum theory of measurement and which appears in Everett's concept as the separation of the single quantum world into classical alternatives.

The identification hypothesis that we are now discussing is not entirely new. It is intimately related to those versions of Everett's interpretation in which the 'many-minds' notion appears. These versions of Everett's interpretation are sometimes given a separate name — the 'many-minds interpretation' (see Refs [30, 27, 23, 28]). We believe that the proposed hypothesis is easier to apprehend and more fruitful, although this appraisal is, of course, quite subjective.

On the face of it, the step made when we adopt the identification hypothesis is not large. But it actually permits seeing the relation between the quantum measurement and the observer's consciousness in a radically different light.

Wherein does the standpoint change when we identify the separation of alternatives with the consciousness? Previously, we knew that these phenomena, which belong to qualitatively different spheres, were nevertheless related to each other. We now believe that this is simply the same phenomenon. Previously, the two spheres had no common elements (although there existed some functional relation between them), and now they have a common element, the consciousness. *The consciousness turns out to be the common part of quantum physics and psychology*, and therefore the common part of the sciences and the humanities.

We make this statement somewhat more precise. The common part of quantum physics and psychology, which may, in the context of quantum physics, be termed the separation of alternatives, is to be identified only with the deepest (or the most primitive) stratum of the consciousness. It is as if this consciousness stratum lies 'at the boundary of consciousness' and is intimately related to the effect of *perception*, i.e., to the transition from the state when something is not realized to the state when it has been realized. To simplify the terminology, we just say that this common part of quantum physics and psychology is consciousness. Only sometimes, whenever necessary, we recall that we are dealing not with the entire diversity of phenomena commonly embraced by the term 'consciousness', but with the intangible that distinguishes the state in which a subject is aware of what is taking place from the state in which she is not.

The identification of consciousness with the separation of alternatives, i.e., of two phenomena from qualitatively different realms, explains why both of these phenomena are poorly comprehensible within the ordinary approach. The understanding is not achieved because each of these phenomena is analyzed only in the context of one realm and an important aspect lying in the other realm is omitted.

In the subsequent discussion, we repeatedly rely on the notion of consciousness as the common part of physics and psychology, which allows us to present a clearer idea of the potentialities concealed in Everett's concept. But first we specify the notion of measurement and alternative measurement results by moving from instantaneous measurements to continuous ones.

9. Representation of alternatives by path corridors

Until now, while on the subject of measurements, we implied instantaneous measurements. That is why the role of alternatives was fulfilled by the state vectors representing the superposition components (in the simplest example that we systematically used, these were $|\psi_1\rangle|\Phi_1\rangle$ and $|\psi_2\rangle|\Phi_2\rangle$). We now consider a more general and more realistic situation where the measurement goes on continuously. In this case, the alternatives may be represented by *path corridors*.

In reality, instantaneous measurements do not exist at all; every measurement has a finite duration. In some cases, the measurement duration is negligible, and it can then be treated as being instantaneous without making a serious error. This is when we are dealing with an instantaneous measurement.

Instantaneous measurements are good for analyzing some features of quantum measurements without complicating this analysis by technical details. This is precisely what we have done until now. In reality, however, measurements most often cannot be treated as being instantaneous: one has to take their duration into account and consider *continuous measurement*. In some cases, the duration of a continuous measurement is very long. This is particularly true of the situation where the 'quantum measurement' is not specially organized by the experimenter but emerges spontaneously as a result of uncontrollable interactions of the quantum system with its environment.[5] In this case, the environment is quite frequently termed a reservoir.

The simplest example of spontaneously occurring continuous measurement is 'quantum diffusion', i.e., the motion of a microscopic particle through some medium. On its way, such a particle permanently interacts with the molecules of

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[5] The time has probably come for a more developed terminology whereby another term will be employed for a spontaneous continuous measurement, but so far there is no such term.

the medium that find themselves near the particle. As a result, the state of the molecules changes, such that the information about the location of the particle and its momentum remains in the reservoir, and a measurement (with some finite resolution) of the particle trajectory takes place. Back reaction of the environment (the reservoir) on the particle may be considered the effect of its measurement by the medium.

Continuous measurement may be represented as a sequence of a large number of instantaneous measurements that occur frequently enough. It may also be described with the aid of the bundles of Feynman paths, which may be visualized as path corridors [31]. A discrete analogue of suchlike corridors are quantum histories [32].

Path corridors play the same part with respect to quantum-mechanical processes as the reduction procedure does with respect to the states of quantum systems. In Feynman's approach, the evolution of a quantum system is described by the integral over all possible paths in the configuration or phase space of this system. When a system undergoes continuous measurement, its evolution is represented by the integral over some corridor of paths. In this case, the corridor of paths itself (denoted by α) corresponds to the measurement result.

The evolution of a system during some finite period is thereby subjected to 'projection' in accordance with the result of continuous measurement. This is quite similar to how the state of the system is, in von Neumann's reduction, projected in accordance with the result produced by the instantaneous measurement of this system. Just as the instantaneous measurement is characterized by the alternative states of the system $\{|\psi_i\rangle|\Phi_i\rangle\}$, so also is continuous measurement characterized by a family of alternatives $\{\alpha\}$, each of which is represented by a path corridor. As with instantaneous measurements, different alternatives are characterized by probabilities, which can be calculated on the basis of quantum mechanics.[6]

For the subsequent discussion, it is significant that *each alternative describes semiclassical motion of the system* whenever the corridors are wide enough and that the corridor α representing some alternative corresponds to some *classical trajectory*.[7] At the same time, quantum effects cannot be completely eliminated. This shows up in that the quantum corridors α coinciding on some interval may differ as a whole, whereas defining some interval of a classical trajectory completely defines the entire trajectory.

An example of a semiclassical quantum state is the coherent state of a family of photons. It is closest to the state of a classical wave. Given the initial conditions, the evolution of the coherent state is well approximated by the evolution of a classical wave, which is determinate, predictable.

An example of an unstable state is the sum or difference of coherent states with strongly different characteristics (the terms may, for instance, correspond to oppositely phased classical waves). In recent years, suchlike states of a small number of photons have been successfully generated in experiments, and therefore it has been borne out experimentally that they quite rapidly decay with the production of coherent (i.e., close-to-classical) states. The decay occurs due to decoherence, which emerges in the interaction with the environment (from which it is impossible to become completely isolated despite any precautions). Because states of this kind are superpositions of two states close to strongly different classical configurations, these states have come to be known as the Schrödinger cats (by analogy with the superposition of a live and dead cat).

Feynman path integrals and integrals over path corridors are mathematically rather complicated (see Refs [6, 31]). However, we do not need specific calculations here, and do not therefore confront mathematical difficulties. In return, in general reasoning, we can take advantage of the apt illustration of a quantum corridor: the system under measurement moves through a corridor defined by the measurement result. Although a corridor in the phase space is implied in general, we may envision a particle moving in a corridor in our ordinary 3-dimensional space for clarity. An alternative in the case of a continuous measurement is the corridor of paths α. And a family of alternatives is a family of corridors $\{\alpha\}$.

10. Classical alternatives: prerequisite to the existence of life

When we consider alternative results of a continuous measurement (alternative path corridors) $\{\alpha\}$ in the framework of the quantum theory of measurement, they should be selected such that they, first, are (approximately) decoherent and, second, (approximately) classical. The decoherence is required for the interference between two different alternative evolutions to be weak and the alternatives be characterized by probabilities instead of probability amplitudes [32, 31]. The classicality requirement is not necessary for the absence of interference [33] but is introduced in order that the theory correspond to experiment.

Indeed, when conducting any measurements, the experimenter may arrive at different alternative measurement results, but each of these results α, according to his observations, is compatible with the laws of classical physics (the Schrödinger cat may be dead or alive, but not a superposition of the live cat and the dead cat). For the theory to describe precisely what is experimentally observed, each corridor α must represent a (semi)classical evolution of the system being measured and its environment.

Therefore, the requirement that the alternatives are classical permits constructing the measurement theory that corresponds to observations. But is it possible to theoretically substantiate this requirement? We now see that it is possible if we adopt Everett's interpretation and its extension, i.e., identify the separation of alternatives with the consciousness.

If we adopt the extended Everett concept, the separation of alternatives is nothing but the consciousness, i.e., the function inherent only in living creatures. Therefore, the entire set of alternatives, i.e., the definition of what states are considered as alternatives, should be considered bearing in mind that this set is to be used by living creatures. Consequently, we can ask the question: what set of alternatives $\{\alpha\}$ is preferred among all possible sets from the viewpoint of living creatures?

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[6] The possibility of characterizing the corridors by probabilities (more precisely, by probability densities) in lieu of amplitudes arises from the fact that they are approximately decoherent, i.e., the interference between them is quite weak [31]. A discrete analogue of the corridor decoherence condition is the compatibility condition for quantum histories [32].

[7] This is true when the corridors $\{\alpha\}$ represent the behavior of not only the system under measurement but also its environment or the device (just as the alternatives $\{|\psi_i\rangle|\Phi_i\rangle\}$ represent the state of both the system being measured and the device in the case of an instantaneous measurement).

Each alternative α describes the behavior of a microscopic system under measurement and its macroscopic environment in the same manner as this behavior is perceived by the consciousness. In this instance, what matters for our reasoning is not that the corridor of paths α represents the system being measured but the fact that it also represents all its (macroscopic) environment, i.e., the whole world. This picture of the world emerges in the consciousness of a living creature. When the world in this picture behaves in accordance with classical laws, it is 'locally predictable' (i.e., the future of some small domain of this world can be predicted with a sufficiently high probability even not knowing what occurs outside this domain). Seeing the predictable world around, a living creature can work out the optimal strategy for survival in this world.

If the alternatives were nonclassical, a picture of an unpredictable world would emerge in the consciousness (in this world, in particular, a significant part might be played by quantum nonlocalities). In this case, the elaboration of the optimal strategy (for a local living creature) would be completely impossible, i.e., life would be impossible in the form known to us. The predictability of evolution, which is characteristic of semiclassical corridors α (which are coarse-grained images of classical trajectories), turns out to be absolutely indispensable in the framework of the extended Everett concept.[8]

Therefore, the classicality of Everett's worlds in the extended Everett concept proves to be indispensable to the very existence of conscious living creatures (conscious at least at the primitive level, sentient). As a matter of fact, in the framework of the extended Everett concept, quantum mechanics sheds light on the very notion of life, of living matter. Unlike inanimate matter, a living creature has the ability to perceive the quantum world in a special way. This world, with its characteristic quantum nonlocality, is perceived by a living creature not as a whole but in the form of individual classical projections. Each of these projections is 'locally predictable'. In each of them, the living creature realizes the scenario termed life, while the very notion of life appears to be impossible without this separation.

Therefore, the choice of precisely the classical evolutions α as the alternatives that separate in the observer's consciousness is favorable to living creatures. This makes plausible the assumption that the phenomenon of separation of alternatives identified with the consciousness is in reality *the capacity that living creatures have developed in the course of evolution* rather than the law of nature (as was usually implied, explicitly or implicitly, in the work on the 'measurement problem'). To be more exact, this capacity had to emerge during the origin of life, because it is only after the emergence of this capacity that the quality needed for survival arose and therefore living creatures appeared. However, this formulation may be insufficiently exact, too utilitarian. More likely, the consciousness (= separation of alternatives) is nothing more nor less than the definition of what life is in the most general sense of the word.

If we assume the concept discussed in this section, it can be said that the classical world does not exist objectively at all and the *illusion of the classical world* emerges only in the consciousness of a living creature. Interestingly, we are led to this physically strange conclusion by physics itself, albeit when we bring it to logical completeness to avoid convenient eclecticism like the Copenhagen interpretation with the reduction postulate.

Different attempts to construct the theory of evolution of living creatures in the framework of the many-worlds interpretation were made in Refs [35–42].

The picture drawn of the functioning of the consciousness and of its role in the survival of a living creature seems so dissimilar to what we directly see in our classical world that there involuntarily arise doubts as to whether this picture can somehow be verified or is doomed to remain merely a theoretical supposition. In the following sections, we discuss how this supposition may be confirmed by observations of the consciousness. Here, we remark that direct physical experiments allow verifying at least the fundamental possibility that such 'quantum consciousness' may indeed exist. This requires constructing the model of the 'quantum consciousness' on the basis of a quantum computer.

Indeed, the quantum states evolving in a quantum computer are superpositions with a large number of components. Each superposition component carries some information (e.g., a binary number) and the evolution of the entire superposition ensures quantum parallelism, i.e., the simultaneous transformation of all these variants of classical information. In the model of quantum consciousness, individual superposition components can model the alternatives into which the consciousness divides the quantum state and the information contained in each component is the state of a living creature and its environment. The problem is to formulate the survival criterion and select the evolution law such that the evolution of every alternative (superposition component) is predictable and survival in this evolution is possible. Of course, the task of constructing this model is by no means simple but is basically solvable using a quantum computer.

It is well known that quantum computers, which promise extraordinary new capabilities, have not been realized, and some experts doubt that they will be realized in the future (see, e.g., review Ref. [43]). However, this applies only to quantum computers with the number of cells of the order of a thousand or more. As for quantum computers with the number of cells around ten, they have already been realized. Evidently, the number of cells attained will increase further, though maybe slowly. It is conceivable that even with these 'low-power' quantum computers, which will be constructed in the relatively near future, it will be possible to realize the model of 'quantum consciousness'.

11. At the edge of consciousness

We consider two assumptions that are basically possible in the framework of Everett's concept and which, if they turn out to be true, would result in a radical change of views on the role of consciousness.

(1) According to Everett's interpretation, there exists an infinite set of Everett's worlds (classical 'realities'), each of which is characterized by some probability (or, in the case of a continuous set, probability density). The probability density is calculated according to conventional quantum-mechanical rules. In the simple example with two alternatives $|\psi_1\rangle$ and $|\psi_2\rangle$, these are the probabilities $p_1 = |c_1|^2$ and $p_2 = |c_2|^2$; in a more complex (and more realistic) picture of continuous measurement, the alternative measurement results (corridors) α are characterized by the probability densities p_α,

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[8] This has something in common with the 'existential interpretation' of quantum mechanics proposed by Zurek [34].

which are also calculated in accordance with quantum-mechanical laws [31].

The probability of a given alternative is quite often interpreted as the fraction of those Everett's worlds in which this alternative is realized, and is identified with the probability that the individual consciousness finds itself in precisely this world, i.e., observes precisely this alternative. Nevertheless, in principle, there remains the possibility to abandon the probability distribution prescribed by quantum mechanics. Several authors have hypothesized (not necessarily in the framework of Everett's interpretation) that the consciousness can affect the probabilities of different alternatives [26, 44, 45].

The conclusion that the probability distribution of alternatives is unambiguously defined by quantum-mechanical laws would be beyond doubt if the selection of one of the alternatives were among those physical laws that are objective and independent of the observer's consciousness. But the separation of alternatives in the framework of Everett's concept is performed by the consciousness (or even more definitely: the separation of alternatives is the consciousness). Even the classicality of the alternatives in the framework of Everett's concept appears to be the necessary condition for the existence of living creatures rather than the law of nature (see Section 10). It would appear reasonable to suggest that the consciousness can affect not only the character of alternatives but also their probabilities, more precisely, the probabilities of which alternative it observes. According to this assumption, the consciousness can increase the probability of finding its way into those classes of Everett's worlds that are preferable to it for some reason.

This assumption may seem to be unacceptable when the probability of an alternative is identified with the fraction of Everett's worlds of the corresponding type (in which this alternative is observed). On the face of it, the number that expresses 'the fraction of the worlds of a given class' should be universal, and must then coincide with the quantum-mechanical probability and may not be different for the consciousness of one observer or another. Were the number of Everett's worlds finite, this would indeed be the case. However, the very notion 'the fraction of the worlds of a given class' is meaningless for the infinite set of worlds, and the argument adduced in favor of the universal character of the probability distribution loses its force. The reason is that an infinite set possesses a paradoxical property: it may be put in a one-to-one correspondence with its own subset. That is why in the case of an infinite set of Everett's worlds, defining different probability distributions on this set is quite admissible and the assumption of the effect of consciousness on the probability distribution is not self-contradictory.

To make this statement pictorial, we assume that an infinite set of the observer's 'replicas' one after another are sent by the consciousness into Everett's world of one type or another in order to fill the infinite set of worlds. For simplicity, we assume that there are only two alternatives, i.e., two world types. Then, for one observer, the replicas may in turn make their way into the type-one and type-two worlds. This corresponds to the following: the probability that a given replica finds its way into the type-one world is equal to $1/2$ (the same is true of the type-two world). The consciousness of the second observer may send its replicas into the same worlds differently: initially, one into the type-one world and the next nine into the type-two world, then one into the type-one world and nine into the type-two world, etc. As a result, for each of them, the probability of finding its way into the type-one world is $1/10$ and the probability of finding its way into the type-two world is $9/10$. However, both the above procedures have the effect that each Everett's world harbors one replica of our observer. Clearly, it then makes no sense to pose the question what is the fraction of type-one worlds (because there are infinitely many worlds).

This reasoning does not prove, of course, that the consciousness can indeed control probabilities but it shows that this assumption is not self-contradictory. It is valid to say: the assumption that the consciousness can make some event probable even though the probability of this event is low according to the laws of physics (quantum mechanics) is consistent. We make an *important improvement on this formulation*: the consciousness of a given observer can make it probable that he will see this event.

When an event whose probability is extremely low according to the laws of physics is made probable by the consciousness, the event taking place may look like a miracle. It is significant that there exists one *absolute limitation* in this case. If the probability of some (mentally constructed) 'classical reality' is equal to zero (i.e., this reality is actually absent in all possible alternative measurement results), the individual consciousness cannot make the probability of finding its way into this reality nonzero. Hence, not every miracle is possible. That which is absolutely forbidden by physical laws (that which takes place only in fairy tales) cannot be realized in any case. And that which is unlikely but possible can be realized 'in reality', even though the probability calculated by physical techniques is very low.

(2) Apart from the assumption about the possible effect of consciousness on the probabilities of alternatives, yet another radical hypothesis proves to be possible in the framework of Everett's concept. It is suggested by the fact that in Everett's concept, the consciousness as a whole (in contrast to its separate components) embraces the whole quantum world, i.e., all its 'classical projections'. In the light of this circumstance, it is conceivable that the individual, subjective consciousness, which lives in some Everett world (in some classical reality), under certain circumstances may nevertheless come out into the quantum world as a whole, and 'look into' other alternatives, other realities. If we assume (as is commonly done in the quantum theory of measurement) that reduction occurs, all alternatives, except one, disappear and there is simply nowhere to 'look into'. But if all alternatives are equally real and the consciousness simply 'separates' their perception for itself, the fundamental possibility to look into any alternative, to become aware of it, does exist.

There is an image that illustrates the splitting of consciousness between alternative classical realities: the blinders put on a horse, such that it cannot look sideward and retains the direction of motion. In precisely the same way, the consciousness puts on the blinders, places 'partitions' between different classical realities in order that each 'component' of the consciousness would see only one of them and would make decisions in accordance with the information coming from only one classical (and hence relatively stable and predictable, i.e., livable) world. However, just as a horse which is wearing blinders can nevertheless look aside by turning its head, so the individual consciousness, which lives in some definite classical reality, should most likely have, despite the partitions, the fundamental ability to look into other classical realities, other Everett worlds. Then, a man is able not only to imagine (which is certainly possible), but also to directly perceive some 'other reality', in which he might also live.

It is even possible to qualitatively characterize that state of consciousness in which this can take place. It is possible to look into other alternatives (or, equally, to go out into the quantum world) only when the partitions between the alternatives vanish or become penetrable. According to the concept under consideration, the emergence of partitions (the separation of alternatives) is nothing but perception, i.e., the emergence of consciousness, its 'origin'. And vice versa, the partitions vanish (or become penetrable) 'at the edge of consciousness', when the consciousness almost vanishes. Suchlike states are commonly called trances.

(3) We make two brief remarks, which are required for the correct understanding of the heart of the problem.

The first remark is intended to specify the interpretation of the hypothesis about 'identification' of the consciousness (commonly considered in the framework of psychology) with the separation of alternatives (the notion of quantum physics). According to this hypothesis, the consciousness (= the separation of alternatives) is a common part of psychology and quantum physics. It becomes possible to study two aspects of this object, the consciousness, to view it from the standpoints of two areas of knowledge different in character: from the standpoints of physics and psychology. Of course, in doing this we see this object differently, and different features of this object turn out to be significant. In physics, while on the subject of the separation of alternatives or the selection of a single alternative, we imply the simplest experiments with the simplest objects, which were intentionally selected among the primitive ones such that they are amenable to investigation by mathematically accurate methods. While on the subject of consciousness as viewed from the standpoint of psychology, we face substantially more complicated and far less clearly defined complexes.

This is of significance, for instance, when we are dealing with the hypothetical possibility of affecting the selection of an alternative with the aid of the consciousness. It is unlikely that the consciousness can have an appreciable effect on what the spin projection turns out to be or in what direction the electron flies. If the consciousness does have the capacity to affect the selection of reality, this most likely applies to those aspects of this reality that are vital to this person (because according to our reasoning, this very phenomenon, the consciousness, emerges because it turns out to be vital to living creatures). If, for instance, a close relative dies in one of these realities and remains alive in another, the conscious subject is highly motivated to select the latter alternative. If he believes in this case that he is able to affect the selection, it is not inconceivable that he will actually increase the probability to some extent that he will witness precisely the latter alternative (whether suchlike possibilities should be used is a separate question, and the answer is not as obvious as it might seem to be).

The 'identification' of the separation of alternatives in quantum physics with the effect of realization in psychology should be understood with this reservation only. Only the deepest layers of the corresponding phenomena are identified, their underlying principle but not their manifestations, which may be extremely unlike in the realms of physics and psychology.

The second remark concerns the new prospects in psychology and in the humanities in general that stem from its relation to physics. We say that the consciousness (the psyche) may, in the framework of the concept involved, have certain features that are not ascribed to it in 'classical' psychology (such as the capability to leave the classical alternative and enter the quantum world, i.e., look into other, alternative, realities or even affect the selection of 'its own' reality). Of course, these hypothetic possibilities call for verification.

However, it would be quite reasonable to attempt to identify these 'new' possibilities with those extraordinary phenomena in the field of psychology, the theory of consciousness, and the psychological practice, which have long been noted, studied by different methods, and even exploited. From this standpoint, the 'new' features of consciousness under discussion might have been known for a long time. If so, some facts in support of the concept under consideration may be found without any additional verification. But in this case, too, careful and cautious work is required to analyze the known facts and to compare them with what might be expected in the framework of Everett's concept.[9] Among the extraordinary phenomena in the realm of consciousness (psyche) that may be related to our concept, we mention, first, special (trance-like) states of the consciousness, the state of the consciousness during sleep in particular, and, second, nonverbal and uncontrollable thinking, which plays an important part in science and which is explicable, in the view of Penrose [49, Ch. 10], on the basis of quantum physics. Very much has been said and written about the special states of consciousness and the state of sleep (in this connection, see the intriguing "Ikonostas" essay by Pavel Florenskiĭ [50, pp. 73 – 198]). The phenomenon of nonverbal thinking is less known. We briefly explain what is implied.

The thinking of a scientist is commonly believed to be a strictly logical and consistent flow of ideas, which are committed to paper or, at any rate, can be stated on paper when wanted with the aid of our ordinary language (with the addition of a number of formulas and drawings). And this is indeed the case at the initial stage of work, when the problem is formulated, and at the final one, when the result is formulated. But the key stage of the scientist's work, which actually yields the result, is the *insight*. And it turns out that the scientist's thinking at this stage quite often (and maybe always) assumes a nonverbal form and proceeds in an uncontrollable manner, independently of his will (however, after the intensive and completely controllable work at the preceding stages).

Roger Penrose, in his book *The Emperor's New Mind* [49], provided examples of important discoveries made in a nonverbal form. Maybe the most striking fact about the testimonies of the great scientists he cited was that at the instant of discovery, in the absence of formal proofs of the verity of their insight, they were absolutely certain that it was true.

This extraordinary and at the same time extremely important phenomenon is impossible to explain in the normal way. It seems to be attributable to the fact that the consciousness enters the quantum world at that moment. Of course, much remains to be done in this area, but some preliminary considerations suggest themselves immediately.

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[9] We mention that there exist other (bearing no direct relation to Everett's concept) quantum-mechanical explanations of extraordinary phenomena in psyche, for instance, attributing telepathy to the quantum correlation of living organisms [46 – 48].

In particular, the idea that a scientific discovery is made 'at the edge of consciousness' leads to the following practical recommendation. After a period of intensive preliminary work on a problem, at the instant when it is required 'to guess the key to its solution', it is expedient to 'switch' the consciousness from this problem for a time to something else (either to another problem, or even simply to relaxation). In this case, the work on the problem actually goes on, but at the level of subconsciousness (or superconsciousness), which is required for the 'discovery', i.e., for the emergence of qualitatively new considerations on the problem. The high efficiency of this procedure has been proven in practice. Similar recommendations are quite frequently encountered in the literature on scientific methodology.

And this is just one example most kindred to a representative of science. There are many other amazing phenomena in the realm of consciousness, and many of them are supposedly certainties. The hope that they will be explained justifies the risk that has to be incurred by making assumptions formally so far unprovable.

(4) While on the subject of extraordinary phenomena in one way or another related to human consciousness, there is no escape from mentioning the forms of their cognition, or even controlling them, that are not scientific. First and foremost, these are different religious beliefs and oriental philosophies. Scientists are fully tempted to exclude this area of human thought as being unscientific, i.e., uncertain. However, one can hardly wave away that which has existed for millennia and represents may be the most stable phenomenon in the sphere of spiritual human life. This stability is most probably an indication that all these unscientific notions rely on something actual, although the actual is infrequently invested with a fabulous form to strengthen its emotional action.

Of interest from this standpoint are oriental philosophies, which directly encourage individuals to work on their own consciousness. We believe that Zen Buddhism and kindred beliefs are most interesting in this respect (about the substantial conceptual proximity of quantum mechanics to 'Middle Way Buddhism', see Ref. [51]). We mention two features of this philosophical–psychological school that seem attractive from the standpoint involved.

First, Buddhism does not require blind belief in the dogmas it proclaims. Disciples are urged to believe only when they assure themselves in the course of work on their own consciousness that the doctrine is correct. Second, Zen Buddhism is distinguished in Buddhism as the direction that specially pursues the elaboration of the 'Zen' idea, and the task to learn to perceive 'Zen' is set before every learner. 'Zen' is a special state or sensation, which is impossible to exactly express by words and which may be characterized approximately as 'the root of consciousness', 'the origin of consciousness', or 'the preconsciousness'. This is an elusive state that precedes the emergence of consciousness. Learners are urged to work on their consciousness until they catch this sensation of 'being between the consciousness and the absence of consciousness'. (The meditation technique, which is rather well known to Europeans, is commonly treated as the skill of switching off one's consciousness, but its true sense is to learn to be between the consciousness and the absence of consciousness.) It is easily seen that the 'Zen' notion bears much resemblance to the deepest or most primitive layer of the consciousness, which may be identified with separation of alternatives in Everett's concept.

12. The need for new methodology

Considering Everett's concept and adopting the hypothesis that the consciousness is identified with the separation of alternatives, we see that the consciousness may have extraordinary properties: the capability for looking into 'other classical realities' and even affecting the selection of the reality in which it lives. It is significant that these features of the consciousness, if they do exist, are in principle observable, they can be discovered and investigated. The extended Everett concept may therefore be verified, i.e., confirmed or refuted, by way of observations. The most significant drawback to Everett's interpretation — the impossibility to verify it in principle — vanishes in this case.

However, it should be realized that the verification in this instance would be quite unusual and would not fall into the pattern of conventional physical methodology.[10] The point is that this verification implies the observation of an individual consciousness. Let us assume that these observations turn out to be in agreement with the predictions of the (extended) Everett concept. Would this be proof of the verity of this concept from the standpoint of physics and physicists? It is no means evident. In physics (and in natural sciences in general), it is agreed that only series of experiments with repetitive results are truth criteria. Moreover, these experiments are to be carried out by different experimenters (to confirm their objectiveness and their independence from the person conducting the experiment). Experiments on one's own individual consciousness or observations of it lack probative force from this standpoint.

To illustrate the originality of the situation, we consider in greater detail what should be expected if the assumption is true that consciousness can affect the probabilities of the observation of different alternatives by this consciousness. As noted in Section 11, zero probability may not transform to a nonzero one, i.e., the consciousness can make probable only that which may take place without its influence, in the natural way, according to physical laws. But this signifies that if some person does have the capacity to ensure the course of events she likes by the effort of her will (her consciousness), she would never be able to guarantee absolutely clearly that she is precisely the one who has so affected the course of events. Should she ensure the realization of unlikely events ('work a miracle') many times, there will always remain the probability, even a low one, that the events have taken this course in a 'natural way', in accordance with ordinary laws.

Therefore, even if 'miracles' of this kind are possible, the evidence that these are indeed 'human-made miracles' and not good luck will never be absolute. And therefore, anyone who decides not to believe in them would have grounds to do so. A skeptic would have the opportunity to doubt even on finding herself, together with the miracle-worker, in that Everett's world where the unlikely event was realized. Moreover, the 'unbeliever' herself would prefer to find herself in the world where the 'miracle' does not occur. For a skeptic, the probability that she sees the realization of

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[10] We recall, however, the possibility of the quantum-computer consciousness model, quite traditional for physics, which was mentioned in Section 10.

an unlikely event with her own eyes therefore remains low.[11]

Thus, if it is assumed that consciousness can modify the alternative probabilities, the situation appears to be very strange. Those who believe in this assumption will have, with an appreciable probability, an opportunity to make certain that it is correct, i.e., that the consciousness does affect the probabilities of events. Those who are unwilling to believe this will, with a high probability, make certain that this does not take place. Skeptics will find themselves in those Everett's worlds where ordinary physical laws, objective and consciousness-independent, exercise undivided rule. But those who prefer to believe in consciousness-worked 'miracles' will find themselves in the worlds where such 'probabilistic wonders' do occur.

When considering the assumption of the effect of consciousness on the probabilities of alternatives, one is forced to accept the fact that the problem of truth criteria should be considered with much greater caution than is generally accepted in natural sciences. This has the following implication: either the Everett concept extended in the above way cannot be included into the realm of physics (and of natural sciences in general), or the methodology of these sciences should be substantially broadened. The new methodology should, first, allow experiments involving individual consciousness or observations of it as the instrument of theory verification and, second, consider the possible effect of a priori aims (inclinations) on the results of observations.[12]

It would be very strange if the above-considered extension of Everett's concept with those new entirely unexpected possibilities it promises is to be rejected only because it proves to be incompatible with the presently existing scientific methodology. Work in this area will most likely be continued if the above-noted possibilities are borne out.

The situation that may arise in this case is perhaps similar to the situation that formed when non-Euclidean geometries were proposed. These new geometries were incompatible with the methodology accepted in mathematics at that time: they necessitated the abandonment of the fifth Euclidean postulate, which was treated as indispensable in geometry. However, it was extremely interesting to pursue the new direction, which opened up quite unexpectedly, and see what came out of changing the methodology by abandoning the fifth postulate. And that opportunity was not missed, of course. It is most surprising that before long, the speculative geometries constructed on this path were endowed with real embodiments, and then this gave birth to the amazingly beautiful and splendid geometrical world that bears the name general relativity and adequately describes the universe.

13. Conclusion

The situation with the 'measurement problem' that has formed in quantum mechanics is unique. It will soon be a century since this problem, which arose unexpectedly, has remained unsolved; however, time and again, on an increasingly broader basis, it is confirmed that the problem still exists and remains to be solved (see, e.g., Refs [53; 54, Ch. 1]). This situation most likely signifies that the solution to the problem is to be expected in a quite unexpected direction or that the character of the solution will be unusual from the standpoint of stereotypes formed in physics. That is why, when estimating the solutions being proposed, one should always be prepared to encounter unexpected solutions so as not to reject the emerging shoots of truth for the reason that they seem unusual. That the problem is nontrivial can be confirmed by viewing the list of great scientists engaged in the problem (we refer to Bohr, Einstein, and Schrödinger [55, 56], to say nothing of Heisenberg, Pauli, and Wheeler, to name but a few).

In our view, the solution will be attained in the direction outlined by Everett's concept, which has attracted considerable attention in the last decades (see review Ref. [23] and the references therein). It is not only abstract problems such as 'the measurement problem' that are involved. In the context of new quantum-mechanical problems, in particular the theory and practice of quantum computers, some researchers (for instance, David Deutsch [37]) resort to Everett's concept as a convenient language for specific investigations. Of course, this is highly subjective, and the majority of physicists employ conventional quantum-mechanical language even in the area of quantum informatics. However, in conceptual problems, Everett's interpretation supposedly furnishes a new quality.

We believe that a helpful viewpoint — in attempts to advance the solving of 'the measurement problem' on the basis of Everett's interpretation — is that which emerges when the consciousness is not merely functionally related to the separation of the quantum world into Everett's alternative worlds, but is completely identified with it (see Section 8 and Ref. [2]). To outline and somewhat develop Everett's concept, we tried to construct a logically consistent chain of reasoning reliant on this identification. It is significant that the thus extended concept may in principle be verified by observations of an individual consciousness. Close (coincident in some points) constructions have been undertaken be several authors, as is seen from the references cited. Especially much has been written (both in the framework of Everett's interpretation and beyond it) about the relation between the consciousness and the state reduction.

To summarize the foregoing, the main points of the above-discussed extended Everett concept and the naturally ensuing consequences can be formulated as follows:

(1) The set of alternatives characteristic of the quantum theory of measurements is interpreted as the set of equivalent projections of the quantum world referred to as Everett's worlds.

(2) Separation of the quantum world into alternatives is identified with the function of living organisms termed the consciousness.

(3) The classical nature of every alternative into which the quantum world is separated by the consciousness is determined by the fact that it ensures the stability and predictability of the ambient world, as perceived by the consciousness, which is the necessary condition for life.

(4) In special states (on the verge of unconsciousness), an individual consciousness gains access to the quantum world

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[11] Here, we are dealing with one of the issues that is counterintuitive and therefore difficult to understand. That is why great care is needed in the analysis of a situation where the results of the effort of a 'miracle-worker' are observed by other people, among which are those who are inclined to believe her and skeptics who are unwilling to believe.

[12] However, a detailed analysis shows that even without the fantastic assumption of the role of consciousness, in the framework of conventional scientific methodology, the inference about the truth always relies on a series of intuitive judgements whose role is commonly not realized in full measure [52].

beyond a single classical projection. This may account for the extraordinary phenomena sometimes observed in the realm of the psyche that play the central part in the nonscientific forms of cognition of spiritual human life (oriental philosophies, religion).

Item 3 in this list is most important. It explains why in the measurement (perception), there occurs splitting of the quantum world into precisely the classical alternatives. The splitting of the quantum world into 'classical realities' (which are actually the mere projections of the solely real quantum world) turns out to be the necessary common property of all living creatures, i.e., the definition of life. In this connection, we note that in his article "What problems of physics and astrophysics seem now to be especially important and interesting at the beginning of the 21st century?" [54, Ch. 1], V L Ginzburg names, among the three 'great' problems, both the interpretation problem of quantum mechanics and the problem of reductionism, i.e., the question of whether the phenomenon of life can be explained on the basis of presently known physics. We have seen that Everett's concept naturally combines both these problems and in a sense reduces one to the other.

Moreover, the last of the three 'great' problems mentioned in Ref. [54, Ch. 1], namely the issue of entropy increase, irreversibility, and the 'time arrow',[13] may also bear relation to the concept under discussion. The point is that the quantum world in this concept obeys the quantum mechanics from which the reduction postulate has been excluded and therefore this world remains reversible. The irreversibility, which manifests itself in the selection of one alternative or another, appears only as the consciousness phenomenon. In other words, characteristic of quantum mechanics, which describes inanimate matter, is the description in terms of the 4-dimensional space – time in which all points in time are treated equally, while the notion of 'the course of time', of the relations between the present, the past, and the future, together with irreversibility, appears only in the description of the life phenomenon.

In the program outlined, as in the field of conceptual quantum-mechanical problems, much cannot be substantiated and has to be accepted as hypothesis, which may produce the impression of amateurishness. However, this character of investigations is actually inevitable in this area of science at the present stage. The situation is as follows. Once the special role of the consciousness in the quantum theory of measurement had come (for scientists engaged in this theory) to be evident, they tried to seek the solution to the problem along the lines physicists were accustomed to: to describe the properties of that material substance which engenders the consciousness (this might be the brain or some structure inside it). In this connection, serious hopes were pinned on the decoherence theory. But it became clear with time that attempts to solve the problem along these lines did not meet with success. Since then, the consciousness has come to be progressively more often regarded as some phenomenon that can be phenomenologically described but cannot be derived from the known properties of (quantum) matter. Clearly, the elements of such a phenomenological description may be introduced into the theory only as hypotheses. Therefore, the presence of hypotheses is more likely an indication that we are dealing with the initial stage of a new direction in science rather than with the amateurishness of the approach.

Work in the context of Everett's concept calls for the extension of methodology and in some sense leads out of the province of physics and even natural sciences in general. This, of course, should cause anxiety and raise debate. However, the problem seems to be extremely important, which justifies even speculative steps. In the event of success in the solution of conceptual problems of quantum mechanics, this science as well as physics entirely, is certain to rise to a qualitatively new level of the understanding of nature. If we are guided by what has already been done in the framework of Everett's concept, physics would be expected to form a fruitful symbiosis with psychology, as well as with other means of cognition of spiritual human life.

The problem of consciousness in quantum mechanics has (and has always had) an important universal cultural aspect: introducing the consciousness as a substantial element of the ideology of quantum physics establishes yet another relation between the cognition realms represented by the sciences and the humanities. In our view, this relation becomes especially close if the extended Everett concept is accepted (in this connection, see Ref. [5]).

We did not set ourselves the task of providing a comprehensive review of the problem but have rather traced the logical chain that seems to show promise. The arguments adduced are more likely to qualitatively direct the way of solution rather than solve the problem. In particular, arduous work is required on the problem of the probabilities of alternatives (in this connection, see Refs [57, 58]). And, nevertheless, central to this 'problem of the century' is, in our view, the search for conceptual solutions rather than mathematical ones. This is the reason why we deliberately avoided details in an endeavor to remain in the context of rather general principles and ideas.

I would like to conclude with words from Wigner's paper [7], which adequately depict the present-day state of the problem although they were written more than forty years ago:

"The present writer is well aware of the fact that he is not the first one to discuss the questions which form the subject of this article and that the surmises of his predecessors were either found to be wrong or unprovable, hence, in the long run, uninteresting. He would not be greatly surprised if the present article shared the fate of those of his predecessors. He feels, however, that many of the earlier speculations on the subject, even if they could not be justified, have stimulated and helped our thinking and emotions and have contributed to re-emphasize the ultimate scientific interest in the question, which is, perhaps, the most fundamental question of all."

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[13] In V L Ginzburg's list, this problem is enumerated first.

References

1. d'Espagnat B *In Search of Reality* (New York: Springer-Verlag, 1983)
2. Menskiĭ M B *Usp. Fiz. Nauk* **170** 631 (2000) [*Phys. Usp.* **43** 585 (2000)]
3. Everett H III *Rev. Mod. Phys.* **29** 454 (1957), reprinted in [59]
4. DeWitt B S, Graham N (Eds) *The Many-Worlds Interpretation of Quantum Mechanics* (Princeton, NJ: Princeton Univ. Press, 1973)
5. Menskiĭ M B *Voprosy Filosofii* (6) 64 (2004)
6. Mensky M B *Quantum Measurements and Decoherence. Models and Phenomenology* (Dordrecht: Kluwer Acad. Publ., 2000) [Translated into Russian (Moscow: Fizmatlit, 2001)]
7. Wigner E P "Remarks on the mind-body question", in *The Scientist Speculates* (Ed. I J Good) (London: Heinemann, 1961) p. 284, reprinted in [59]
8. Von Neumann J *Mathematische Grundlagen der Quantenmechanik* (Berlin: J. Springer, 1932) [Translated into English: *Mathematical Foundations of Quantum Mechanics* (Princeton, NJ: Princeton Univ. Press, 1955); translated into Russian (Moscow: Nauka, 1964)]
9. Zeh H-D *Found. Phys.* **1** 69 (1970)
10. Zurek W H *Phys. Rev. D* **24** 1516 (1981)
11. Zurek W H *Phys. Rev. D* **26** 1862 (1982)
12. Joos E, Zeh H-D *Z. Phys. B* **59** 223 (1985)
13. Giulini D et al. *Decoherence and the Appearance of a Classical World in Quantum Theory* (Berlin: Springer, 1996)
14. Bell J S *Speakable and Unspeakable in Quantum Mechanics* (Cambridge: Cambridge Univ. Press, 1987)
15. Bell J S *Physics* **1** 195 (1964), reprinted in [14]
16. Aspect A, Grangier P, Roger G *Phys. Rev. Lett.* **47** 460 (1981)
17. Aspect A, Dalibard J, Roger G *Phys. Rev. Lett.* **49** 1804 (1982)
18. Einstein A, Podolsky B, Rosen N *Phys. Rev.* **47** 777 (1935)
19. Chernavskiĭ D S *Sinergetika i Informatsiya*: *Dinamicheskaya Teoriya Informatsii* (Synergetics and Information: Dynamic Information Theory) (Moscow: Nauka, 2001)
20. Belinskiĭ A V *Usp. Fiz. Nauk* **173** 905 (2003) [*Phys. Usp.* **46** 877 (2003)]
21. Popov M A *Usp. Fiz. Nauk* **173** 1382 (2003) [*Phys. Usp.* **46** 1307 (2003)]
22. Panov A D *Usp. Fiz. Nauk* **171** 447 (2001) [*Phys. Usp.* **44** 427 (2001)]
23. Vaidman L "The many-worlds interpretation of quantum mechanics", in *Stanford Encyclopedia of Philosophy* (Electronic Resource) (Ed. E N Zalta) (Stanford, Calif.: Metaphysics Research Lab, Centre for the Study of Language and Information, Stanford Univ., 2002); http://plato.stanford.edu/archives/sum2002/entries/qm-manyworlds/
24. Tegmark M *Fortschr. Phys.* **46** 855 (1998)
25. Mensky M B, von Borzeszkowski H *Phys. Lett. A* **208** 269 (1995); quant-ph/0007091
26. Squires E *The Mystery of the Quantum World* 2nd ed. (Bristol: IOP Publ., 1994)
27. Lockwood M *Brit. J. Philos. Sci.* **47** 159 (1996)
28. Whitaker A "Many minds and single mind interpretations of quantum theory", in *Decoherence*: *Theoretical, Experimental, and Conceptual Problems*: *Proc. of a Workshop, Bielefeld, Germany, 10–14 November 1998* (Eds P Blanchard et al.) (Berlin: Springer, 2000) p. 299
29. Stapp H P *Found. Phys.* **31** 1465 (2001)
30. Albert D, Loewer B *Synthese* **77** 195 (1988)
31. Menskiĭ M B *Usp. Fiz. Nauk* **173** 1199 (2003) [*Phys. Usp.* **46** 1163 (2003)]
32. Gell-Mann M, Hartle J B *Phys. Rev. D* **47** 3345 (1993)
33. Paz J P, Zurek W H *Phys. Rev. D* **48** 2728 (1993)
34. Zurek W H *Philos. Trans. R. Soc. London A* **356** 1793 (1998)
35. Albert D Z *Quantum Mechanics and Experience* (Cambridge, Mass.: Harvard Univ. Press, 1992)
36. Chalmers D J *The Conscious Mind in Search of a Fundamental Theory* (New York: Oxford Univ. Press, 1996)
37. Deutsch D *The Fabric of Reality*: *the Science of Parallel Universes and Its Implications* (New York: Allen Lane, 1997) [Translated into Russian (Izhevsk: RKhD, 2001)]
38. Donald M J *Philos. Trans. R. Soc. London A* **427** 43 (1990)
39. Lehner C *Synthese* **110** 191 (1997)
40. Lockwood M *Mind, Brain, and the Quantum*: *the Compound T* (Oxford: B. Blackwell, 1989)
41. Penrose R *Shadows of the Mind*: *a Search for the Missing Science of Consciousness* (Oxford: Oxford Univ. Press, 1994)
42. Saunders S *Phys. Lett. A* **184** 1 (1993)
43. Valiev K A *Usp. Fiz. Nauk* **175** 3 (2005) [*Phys. Usp.* **48** 1 (2005)]
44. Eccles J C *How the Self Controls its Brain* (Berlin: Springer-Verlag, 1994)
45. Beck F, Eccles J "Quantum processes in the brain: A scientific basis of consciousness", in *Neural Basis of Consciousness* (Adv. in Consciousness Res., Vol. 49, Ed. N Osaka) (Philadelphia, PA: John Benjamins Publ., 2003) p. 141
46. Josephson B D, Pallikari-Viras F *Found. Phys.* **21** 197 (1991)
47. Villars C N *Psychoenergetics* **5** 1 (1983)
48. Lovelock J E *Nature* **344** 100 (1990)
49. Penrose R *The Emperor's New Mind*: *Concepting Computers, Minds, and the Laws of Physics* (New York: Penguin Books, 1991) [Translated into Russian (Moscow: URSS, 2003)]
50. Florenskiĭ P *Izbrannye Trudy po Iskusstvu* (Selected Works on Art) (Moscow: Izobrazitel'noe Iskusstvo, 1996)
51. Mansfield V "Possible worlds, quantum mechanics, and Middle Way Buddhism", in *Symposium on the Foundations of Modern Physics, Joensuu, Finland, 13–17 August 1990* (Eds P Lahti, P Mittelstaedt) (Singapore: World Scientific, 1991) p. 242
52. Feĭnberg E L *Dve Kul'tury. Intuitsiya i Logika v Iskusstve i Kul'ture* (Two Cultures. Intuition and Logic in Art and Culture) 3rd ed. (Fryazino: Vek-2, 2004) [Expanded German edition: *Zwei Kulturen. Intuition und Logik in Kunst und Wissenschaften* (Berlin: Springer-Verlag, 1998)]
53. Markov M A *O Trekh Interpretatsiyakh Kvantovoĭ Mekhaniki* (On Three Interpretations of Quantum Mechanics) (Moscow: Nauka, 1991)
54. Ginzburg V L *O Nauke, o Sebe i o Drugikh* (About Science, Myself, and Others) 3rd ed. (Moscow: Fizmatlit, 2003) [Translated into English (Bristol: IOP Publ., 2005)]
55. Bohr N "Discussion with Einstein on epistemological problems in atomic physics", in *Albert Einstein*: *Philosopher–Scientist* (The Library of Living Philosophers, Vol. 7, Ed. P A Schilpp) (Evanston, Ill.: Library of Living Philosophers, 1949) p. 200; reprinted in [59] [Translated into Russian in *Atomnaya Fizika i Chelovecheskoe Poznanie* (Moscow: IL, 1961) p. 51]
56. Schrödinger E *What is Life*? *The Physical Aspect of the Living Cell* (Cambridge: The Univ. Press, 1944) [Translated into Russian (Izhevsk: RKhD, 1999)]
57. Hartle J *Am. J. Phys.* **36** 704 (1968)
58. Rubin M A *Found. Phys.* **33** 379 (2003); quant-ph/0209055
59. Wheeler J A, Zurek W H (Eds) *Quantum Theory and Measurement* (Princeton, NJ: Princeton Univ. Press, 1983)