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Quantum measurements, the phenomenon of life, and time arrow: three great problems of physics (in Ginzburg's terminology) and their interrelation

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Contents

Abstract. **Relations existing among "the three great problems" of physics (as enumerated by Ginzburg) — interpretation of quantum mechanics, the time arrow, and reductionism (reducing the phenomenon of life to physics) — are discussed and shown to substantially depend on how the first of them is solved, i.e., which interpretation of quantum mechanics is adopted. The Copenhagen interpretation, the Everett ('many-worlds') interpretation, and Extended Everett Concept proposed by the author are considered.**

1. Introduction

At the end of Vitalii Ginzburg's list of the most important problems in physics, we see three problems that are not included on the major list. Listed separately, they are termed by Ginzburg as "the three great problems". These are the interpretation of quantum mechanics, the time arrow (i.e., the irreversibility of time appearing despite the reversibility of the main dynamic equations), and reductionism (i.e., the possibility of reducing the phenomenon of life to physics). Perhaps these are the most challenging problems faced by physicists and, at the same time, the most interesting ones, or at least the most exciting. Much has been written concerning these problems and certainly many significant results have been achieved. It is definitely impossible to give a complete overview of "the three great problems" in this short presentation. I will only discuss this subject from a single viewpoint which can be characterized as follows.

I will start the analysis from the first of the three great problems, which is the interpretation of quantum mechanics. I will try to show how the relationships among the three great problems look depending on the way the first one is solved, i.e., by one interpretation of quantum mechanics or another.

Whenever one speaks about the *interpretation of quantum mechanics*, the question is always closely related to quantum measurements, since it is the description of measurements of quantum systems that evokes the problem of the interpretation of quantum mechanics. One can therefore reformulate the first great problem as the problem of *quantum measurement theory*. This theory, along with the interpretation of quantum mechanics, is now intensively discussed all over the world, in particular, in connection with quantum informatics. The reason is that the applied field of research called quantum information science is based on the same principles as quantum measurement theory, the principles that are closely related to the interpretation of quantum mechanics. Due to the importance of quantum informatics applications, the last decades have seen a revival of interest in the interpretation of quantum mechanics and the rapid advancement of the relevant field of research.

At the center of modern studies in this field is the interpretation of quantum mechanics suggested by H Everett in 1957 and often referred to as the '*many-worlds*' *interpretation* [1, 2]. At the same time, the *Copenhagen interpretation*, the oldest and the best-verified, has received wide recognition among physicists. It was developed by Niels Bohr in the

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course of intensive and difficult discussions with other founders of quantum mechanics, in particular, with Albert Einstein. These two interpretations are qualitatively different, while other numerous interpretations are just versions of these two and differ from them only in details.

In my *Physics-Uspekhi* paper of 2000 [3], I made an attempt to further develop Everett's interpretation. Research in this area was continued later. The resulting *Extended Everett Concept* (EEC), in contrast to the original interpretation by Everett, leads to new predictions that relate to the work of consciousness; moreover, these predictions find experimental confirmation. Below, in the analysis of "the three great problems" I will rely on (1) the Copenhagen interpretation, (2) Everett's interpretation, and (3) the EEC.

In fact, these concepts are the three ways to solve the first of "the three great problems". After briefly characterizing each of the three different approaches to the conceptual problems of quantum mechanics, I will try to trace how the remaining two of "the three great problems" and the relationships among all three look in view of different approaches. In other words, interpretation of quantum mechanics will be the starting point for the discussion of, first, the phenomenon of life (and the question of whether it can be explained in the framework of quantum physics) and, second, the 'time arrow' problem (i.e., the question why, despite the reversibility of quantum-mechanical evolution, there is still irreversibility in quantum mechanics).

2. 'Ginzburg's problems'

One of the distinguishing features of Ginzburg's scientific style is what I would call a systematic approach to science. This systematic approach reveals itself in his work on the list of the most important problems in physics. In addition to solving specific problems, he has constantly analyzed physics as a whole, as well as science as a whole, and has always looked for the points of growth in physics and in science in general. This is certainly very important since the future of science grows from current problems. A today's problem may tomorrow become the center and essence of all physics and a source of new achievements. In any case, this is true for "the great problems", against which scientists have struggled for many decades, not losing interest but, on the other hand, not considering the achieved progress as a final solution.

Thus, "the three great problems", which Ginzburg mentions at the end of his list, can be formulated as the following questions:

- Interpretation of quantum mechanics: what happens during measurement?
- The phenomenon of life and reductionism: what is life from the viewpoint of physics?
- The time arrow: where does irreversibility come from?

The first problem is called the problem of the interpretation of quantum mechanics but in fact is an attempt to find out what happens during measurement. Why during measurement? Because conceptual problems (paradoxes) of quantum mechanics present themselves when we try to analyze the process called measurement in terms of quantum mechanics. In classical physics, the description of measurement is very simple, in fact, trivial (of course, only in principle, when purely technical issues related to the measurement devices are ignored). However, it turns out that the quantum-mechanical description of measurement causes paradoxes. It is not at all evident what 'measuring a quantum system' means and what happens in such a measurement.

The second problem is the phenomenon of life and reductionism. What is life from the viewpoint of physics? Can one explain the phenomenon of life based on the laws of physics? There is no evident answer to this question. In any case, the numerous attempts to 'derive the phenomenon of life from physics' (together with other natural sciences) have enjoyed no success so far.

The third great problem, according to Ginzburg, is the origin of the time arrow. Where does irreversibility come from? In quantum mechanics, which is the most fundamental science, all equations are reversible in time. How, then, does irreversibility appear?

As I have already mentioned, I will start the analysis by choosing one interpretation of quantum mechanics or another and discuss the other two problems and especially the relationship among all three problems from the viewpoint of the chosen interpretation. In this connection, it is important to note that various interpretations of quantum mechanics are, in fact, various levels of describing quantum measurement. Sometimes one says: let us find which interpretation is the correct one. In my opinion, this is the wrong question. Various interpretations are different descriptions of the same process, the quantum measurement. All descriptions are correct but they 'decode' this process on various levels, uncovering the mechanism of measurement to a greater or lesser extent.

Starting from the famous paper by Einstein, Podolsky, and Rosen [4], it has become more and more evident that to give an interpretation of quantum mechanics means to explain how reality is understood in quantum mechanics or, in other words, what the *quantum reality* is. Accepting one interpretation or another means explaining the quantum reality in one way or another. This, however, can be done on various levels. More primitive levels (including the Copenhagen interpretation) are rather easy for understanding and convenient in practice, but their description of the essence of quantum reality is not sufficiently exact. Interpretations of higher level (including Everett's) express this essence more precisely but are more *arduous* for understanding and produce more difficulties than help for practising researcher in quantum physics (for instance, for solving typical quantum-mechanical problems). This explains why Everett's interpretation was accepted with such difficulty. Nevertheless, it has come into great demand over the last decades, in particular, due to the development of quantum information science.

A more exact interpretation does not cancel a less exact one, since different interpretations do not influence the mathematical base of quantum mechanics; calculations and predictions for specific experiments are made according to the same recipes regardless of the interpretation. As a consequence, calculations do not require complicated interpretations like Everett's one. The Copenhagen interpretation is quite sufficient. But if one takes into account the fact that the Copenhagen interpretation has logical defects, then, for more exact reasoning, one has to turn to other interpretations and, first of all, to Everett's. However, as we will see in Sections 7 and 8, moving to more profound interpretations of quantum mechanics not only restores the logical completeness of this science but also allows one to explain important facts relating to the work of the consciousness (i.e., at first sight, having no relation to quantum physics) that have found no explanation up to now.

3. Relations among "the three great problems" at various levels of measurement description

Let us begin with some reasoning leaping ahead. We will briefly characterize the relationships among the three great problems without dwelling on the proofs of these relationships. This reasoning can be illustrated with the scheme shown in Fig. 1.

Quantum measurement and the time arrow — what is the relation between them? It is very simple. This relation was discussed long ago, it is evident even in the framework of the Copenhagen interpretation. The point is that if a measurement is performed in a quantum system, then some jump occurs, an irreversible change in the state of the system. This change is called the state reduction or the wave function collapse. Such an irreversible change in the state resulting from the measurement occurs only in quantum physics; a measurement in classical physics does not lead to irreversibility (although irreversibility may emerge in classical physics for other reasons).

Before the measurement, only the probabilities of various measurement results can be predicted, even if the state of the system is fully known. During the measurement, a single result is chosen from the set of all possible (alternative) measurement results. In this case, the state of the system is irreversibly changed. After the measurement, the system cannot return to the state in which all measurement outcomes are possible. This way, a measurement brings irreversibility to quantum mechanics, which is absent in a usual evolution, with no measurements involved.

This reasoning is valid in the framework of the Copenhagen interpretation. However, if we consider a more complicated interpretation, Everett's interpretation (I will say later why it arises and why the Copenhagen interpretation is not sufficient), then it turns out that the observer's consciousness should be included in the measurement. Without it, the measurement description is not complete. Thus, new relationships among the three problems appear.

First of all, a relation appears between quantum measurement and consciousness. This relation is hardly expected from the usual physics viewpoint. Indeed, consciousness is a phenomenon of living creatures. This notion is simply absent in the world of abiotic physical systems that is the subject of physics. By introducing the consciousness of the observer into the measurement theory, Everett's interpretation of quantum mechanics establishes a direct relation between quantum measurement (and, hence, quantum mechanics in general) and the phenomenon of life. This seems to be completely foreign to physics, at least in its simple version, which one could expect to describe measurement. Therefore, it turns out that quantum mechanics and the phenomenon of life are closely related and the measurement theory in quantum mechanics proves to be not so simple.

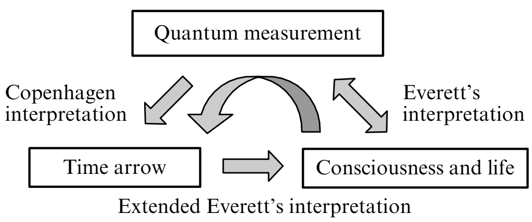

Figure 1. Description of the quantum measurement on a higher level reveals a richer structure of relations between the three great problems.

In addition, in Everett's interpretation the irreversibility of measurement arises only in the picture drawn by the observer's consciousness. Hence, measurement leads to the time arrow only if the role of consciousness is taken into account (see the bent arrow in Fig. 1).

If we pass to the Extended Everett Concept (later we will see what it states and why this extension is necessary), then another arrow appears, another relation among the above three problems — connection of the time arrow with consciousness and life. Indeed, in the framework of the EEC one can understand how a decrease in entropy can occur in life, while the rule for abiotic systems is the entropy increase. For life, self-organization is typical. Life develops, and its evolution is directed not towards greater chaos (an entropy increase) but towards greater order (an entropy decrease). In the living world, the time arrow also exists, but the entropy behavior with respect to the time arrow is strange: the entropy decreases.

This is caused by the fact that the very existence of a living creature depends on what will happen in the future. The notion of aim (the basic aim is survival) is inherent in living world and hence the related feeling of time running: the future is different from the past and present (which separates the future from the past).

Summarizing (and leaping ahead, since we have not proved anything so far), we see that solving the first problem leads to a deeper understanding of the other two, according to the following scheme:

- Quantum measurement
  $\Rightarrow$ the role of the observer's consciousness
- $\Rightarrow$ • Phenomenon of consciousness and phenomenon of life
  $\Rightarrow$ quantum reality
- $\Rightarrow$ • Reversibility of the quantum world and the subjective feeling of time running.

4. Copenhagen interpretation: reduction of the state

What is the Copenhagen interpretation? How does it describe a measurement in a quantum system? Briefly, this can be formulated in the following way (Fig. 2). Let the state of a quantum system before the measurement be the superposition state $c_1\psi_1 + \ldots + c_n\psi_n + \ldots$, where the components $\{c_n\psi_n\}$ correspond to various measurement results that can be obtained with a given instrument. Then, after the measurement the system is brought into a single definite state ψ_i, one of those forming the superposition. This effect, i.e., selection of one of the components and the disappearance of all other ones, is called *reduction of the state*, or the *wave function collapse*. This change in the state of a quantum system is stepwise and irreversible. A measurement causes a

$$\begin{array}{c} c_1\psi_1 + \ldots + c_n\psi_n + \ldots \\ \downarrow \\ \psi_i \end{array}$$

Figure 2. Reduction postulate: when a quantum system is measured, its initial state changes in such a way that a single component of the superposition survives, the one that corresponds to the measurement result.

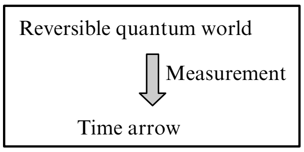

Figure 3. The reduction postulate means that a measurement of a quantum system leads to an irreversible change in its state, i.e., a quantum measurement leads to irreversibility (creates the time arrow).

jump from a superposition state into a state given by a single component of the superposition.

Thus, in the framework of the Copenhagen interpretation a measurement of a quantum system is an irreversible process. Measurements (and not only ones that are specially organized but also those that occur spontaneously due to the environment or a thermostat) introduce irreversibility into quantum mechanics. Hence, the first relation between the great problems is established: measurement brings the time arrow into quantum mechanics. In a theory, whose equations are symmetric with respect to the time reversal, irreversibility appears (Fig. 3). This kind of irreversibility has been intensively discussed in the literature, and a review can be found in the monograph [5].

In the Copenhagen interpretation, the state reduction was postulated. A mathematically strict formulation of this postulate was first given by von Neumann, and therefore the reduction postulate is also called the *von Neumann postulate*. If one postulates that a measurement causes reduction, i.e., one of the superposition components is selected (with a corresponding probability), then calculations based on this postulate will not lead to errors. [1] In this sense, such a postulate makes quantum mechanics efficient.

If the reduction postulate is rejected, a problem appears. We understand very well how a closed system behaves, but if such a system is measured and still exists after the measurement, then a question arises: what is the state of the system after the measurement? Indeed, to find out what happens with the system later (during a time interval after the measurement), we need to know its state immediately after the measurement.

If this question is answered the same way as in the reduction postulate, then calculations provide predictions that are confirmed experimentally. In this sense, the reduction postulate leaves no doubts. The genius of N Bohr allowed him, in particular, to develop such a simple formulation of quantum mechanics (the Copenhagen interpretation) that could efficiently solve quantum-mechanical problems despite the conceptual gaps that, as many researchers understood, still remained in this science.

5. Decoherence: reduction is impossible

However, the reduction postulate itself can be doubted. And it was doubted from the very beginning, but these doubts became more solid after the development of the *decoherence* theory. The decoherence theory describes the measurement process without invoking any special postulate like the reduction one, and only within the framework of quantum mechanics where evolution is always described by the time-reversible Schrödinger equation.

To move to this description of measurement, it is sufficient to recall that a measurement is the interaction of the measured system with another system, which can be called the measuring instrument. This second system can be considered to be the environment of the system under measurement. Interaction of the system under measurement with its environment can be described in the framework of standard quantum mechanics based on the Schrödinger equation and not involving the reduction postulate. In this case, one should try, in the framework of standard quantum mechanics and without the reduction postulate, to answer the question: what happens when a measurement is performed on a quantum system?

This turns out to be possible. An appropriate consideration shows that *entanglement*, or *quantum correlation*, appears between the system under measurement and its environment, and the state of the measured system, taken separately, is crucially changed as a result of the measurement (i.e., its interaction with the environment). One says that in this case the measured system undergoes *decoherence*.

Why is this change in the state of the measured system called decoherence? Because the system subjected to measurement (interacting with a measuring instrument) loses quantum coherence. The information about the relative phases of separate wave function components is lost. As a result, if the state of the system before the measurement was a *pure one* and was described by a wave function (a state vector), after the measurement it becomes *mixed* and is described by a density matrix.

Most probably, the physical essence of measurement was already clear to the founders of quantum mechanics, but at that time it was neither stressed nor formulated in detail. Therefore, it was much later that this science, the decoherence theory, was rediscovered by the scientific community. The phenomenon called decoherence became widely known starting from 1982, when the paper [7] by W H Zurek appeared. After that, decoherence was extensively discussed in the literature, and its understanding gradually deepened.

It turned out that physicists have been constantly facing this phenomenon while studying various systems and their interactions, but it was not considered to be a special class of quantum-mechanical processes. Zurek described this class of processes from the viewpoint of quantum measurement theory and thus revealed its special role. After that, physicists started to actively study the decoherence effect.

In the course of these studies, it developed that decoherence had been understood and very well described as early as 1970 by Dieter Zeh, a German physicist [8]. However, neither the paper [8] nor later works by Zeh and his disciples were noted by the scientific community. In 1979, decoherence was described by the author of the present paper in the framework of a completely different phenomenological approach, based on Feynman's path integrals [9, 10]. Still, it was only many years later that various ways of describing this process were brought together and compared, and all works were understood as relating to the same class of phenomena which was called decoherence. The very term 'decoherence' was introduced in a paper by M Gell-Mann and J B Hartle [11] only in 1990. The modern state of the decoherence theory is well described in the frameworks of various models in the book

[1] Of course, a more realistic description of quantum measurements requires some purely technical generalizations, in particular, the concepts of a soft (inaccurate) measurement and a continuous measurement (see, for instance, Ref. [6]), but these refinements do not change the essence of the questions we are discussing.

$$(c_1\psi_1 + \ldots + c_n\psi_n + \ldots)\,\Phi_0$$
$$\Downarrow$$
$$c_1\psi_1\Phi_1 + \ldots + c_n\psi_n\Phi_n + \ldots$$
$$= \;\Psi_1 \;+ \ldots + \;\Psi_n + \ldots$$

Figure 4. Due to the linearity of quantum mechanics, the state reduction is impossible. During a measurement there occurs only 'entanglement', or quantum correlation, between the measured system and the instrument, leading to the decoherence of the measured system.

[12] by Zeh and his students, while its description from the viewpoints of different phenomenological approaches can be found in the book [6] (in these approaches, the environment is not considered explicitly and its influence on the system is taken into account phenomenologically.)

Let us discuss in more detail what happens during a measurement of a quantum system. How can one consider measurement in the framework of conventional quantum mechanics? This is illustrated in Fig. 4. Similarly to our previous reasoning, we assume that before the measurement the system resides in a superposition state $c_1\psi_1 + \ldots + c_n\psi_n + \ldots$, but now we will take into account not only the system under measurement, but also the measuring instrument, or the environment of the system. Let the state of the environment before its interaction with the system (i.e., before the measurement) be described by the vector Φ_0. Then, the state of the whole system, whose subsystems are both the measured system and the environment, before the measurement is given by the vector $(c_1\psi_1 + \ldots + c_n\psi_n + \ldots)\Phi_0$.

Now, let us consider the interaction between the measured system and its environment and ask the following question: what happens after the interaction? How do the states of the system and its environment change? It turns out that under some natural assumptions about the interaction, the conventional quantum mechanics makes the state of the total system change in the following way:

$$(c_1\psi_1 + \ldots + c_n\psi_n + \ldots)\,\Phi_0 \\ \rightarrow c_1\psi_1\Phi_1 + \ldots + c_n\psi_n\Phi_n + \ldots\,.$$

Here, Φ_n denotes the state of the measuring instrument that is interpreted by the experimentalist[2] as indicating the system to be in the state ψ_n.

We now see that the state vector of the system under measurement and the state vector of the measuring instrument (environment) do not exist separately. Instead, there is only the state of the total system, in which the measured system and the measuring instrument are correlated. This 'nonfactorable' state (which cannot be factored into a product of the state vector of the system and the state vector of the instrument) is called *entangled*. In such a state, there is a *quantum correlation* between the system and the instrument. The correlation can be formulated in the conditional mood: if the system resides in the state ψ_n (in the nth component of the superposition), then the instrument is in the state Φ_n. However, one should realize that this conventional phrase does not reflect the specific features of quantum correlation, distinguishing it from correlations feasible in classical systems.

It is important for us that in this description all components that were present in the superposition before the measurement are still retained after the measurement (although each component changed). The disappearance of all components except one, which was to occur according to the reduction postulate, did not happen here. Thus, the usual quantum-mechanical treatment of the measurement event shows that all superposition components survive the measurement. All that happens is the phenomenon termed 'entanglement', or quantum correlation, between the system under measurement and the instrument (the environment).[3]

It is important — and later I will discuss it from another viewpoint — that the total system, i.e., the measured system and its environment, resides in a superposition state after the measurement. In Fig. 4, this circumstance is highlighted in the bottom line: it is not the structure of each component in the superposition that is important but the fact that all superposition components 'survive' the measurement.

Let us summarize our reasoning where measurement is considered as interaction. If a superposition exists at some stage, it will be further retained, and this follows from the linearity of quantum-mechanical evolution. Each term in the superposition may change somehow, but all terms will still be present, none of them becoming zero. There is no reduction, i.e., selection of a single component and the disappearance of the other ones. This is dictated by quantum mechanics. *Quantum mechanics excludes reduction.*

6. Everett's ('many-worlds') interpretation: there is no reduction

Thus, if we trust quantum mechanics, i.e., consider the evolution of the system to be always described by the Schrödinger equation, then reduction should be somehow excluded. How can one do it? The answer was given by an interpretation of quantum mechanics proposed by H Everett [1, 2] in 1957.

The logic upholding Everett's interpretation is very simple. Let us start from quantum mechanics. Quantum mechanics dictates that no reduction is possible. Relying on quantum mechanics, we accept the statement: there is no reduction, all components of a quantum superposition survive during the evolution, including the measurement process (see the bottom line in Fig. 4).

However, if one accepts this simple logic, it is necessary to explain how it happens that the observer sees just a single measurement result corresponding to just a single component of the superposition.

A measurement can lead to different results, which exclude each other in the consciousness of the observer — the 'alternatives'. All alternatives are still present in the superposition, and Everett's interpretation assumes that

[2] The description of the environment is maximally idealized here, but without loss of any significant features of the process. In reality, the Φ_0 vector represents only some part of the environment, the one that directly interacts with the system under measurement; this part of the measuring instrument is usually called a meter. In the general case, before the interaction (measurement) it can be in any one of the set of states $\Phi_0^{(\lambda)}$ (which become, respectively, $\Phi_n^{(\lambda)}$ for the nth measurement result), or in a mixed state $\sum_\lambda p_\lambda \Phi_0^{(\lambda)}\Phi_0^{(\lambda)\dagger}$.

[3] Sometimes, one tries to justify the reduction postulate by claiming that the measuring instrument is macroscopic and its evolution is classical. However, the classical description of any system is approximate (compared to the quantum one) and in no way cancels the exact description in the framework of quantum mechanics. (It only makes the quantum approach too detailed when only a crude description of a system is necessary.) Therefore, a conclusion made in the framework of an exact description cannot be disproved by means of an approximate description.

after the measurement they are still kept in the description of the state. How can one understand this? How can one combine this with the everyday experience of an experimentalist who always observes just a single measurement result and not a superposition of results, only a single alternative Ψ_i and not a superposition $\sum_n \Psi_n$ of alternatives, as in the bottom line of the scheme in Fig. 4?

It should be noted that now an important role in the reasoning is played by the observer or, more precisely, the *observer's consciousness*, and the interpretation of the fact that all superposition components are retained can involve this notion, the observer's consciousness. It is important that the picture formed in the consciousness of the observer (and which is represented by the Ψ_i vector) is a purely classical one. This is a picture of a classical world, and it is always only a single one among the alternative pictures of the classical world that is present in the consciousness of the observer. (In terms of a measurement procedure, different pictures of the classical world correspond to different positions of the measuring instrument pointer, and the observer always sees just a single position of the pointer.) In Everett's interpretation, one should explain how this can agree with the fact that a superposition contains all alternatives $\{\Psi_n\}$ corresponding to various pictures of the classical world.

To overcome this controversy, the following statement is assumed in Everett's interpretation. All superposition components exist and describe different alternatives, i.e., alternative measurement results or alternative classical (quasiclassical) states of the quantum world, but *consciousness separates the alternatives* (Fig. 5). Consciousness perceives these alternatives separately. If a person observes one of the alternatives, she cannot see the other ones at the same time.

Separation of the alternatives by the consciousness is a formulation of Everett's interpretation that is convenient for our purposes. There are also other formulations, for instance, the one where different classical worlds exist, *Everett's worlds*, which correspond to all possible alternatives. According to this formulation, each of the observers exists in each of Everett's worlds (in other words, an observer has twins in each of Everett's worlds). This formulation is very widely spread because of its explicitness, but actually it sometimes causes misunderstanding as it contains a certain inaccuracy: one should speak not of different classical worlds but of different classical states of a single world and about the superposition of these states.

If we accept the statement about the alternatives being separated by the consciousness, then in the description of the picture in the observer's consciousness the same effect occurs as predicted by the reduction postulate: subjectively, the observer will see (recognize) only one of the alternative classical pictures of the world. However, now we have managed to combine it with linear quantum mechanics: all alternatives exist in reality but they are separated in the consciousness. Consciousness, similarly to the state of the material world, also consists of something like multiple components, which subjectively seem to be mutually exclusive. These components reflect the alternatives.

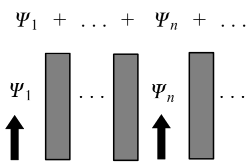

Figure 5. Everett's interpretation: reduction (disappearance of all alternatives but one) does not happen but consciousness separates classical alternatives by perceiving them separately.

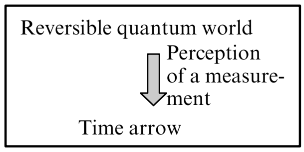

Figure 6. According to Everett's interpretation, irreversibility appears in a quantum measurement due to the perception of a measurement result.

What new results does it provide for the relations among "the three great problems"? How do these relations change if one moves to Everett's interpretation in which all alternatives are assumed to be equally real but separated in the consciousness? The relationships among the three great problems remain almost the same as in the case of the Copenhagen interpretation, with the only exception being a single nuance (Fig. 6). Now, one should say that the time arrow does not objectively exist in the quantum world but it only appears in the consciousness of the observer.

In reality, i.e., in the objectively existing world, all superposition components, all alternatives, are retained (stay equally real), and the evolution of their superposition is quite reversible. However, consciousness perceives these alternatives separately, and in the consciousness this leads to a picture of an irreversible process, namely, the choice of a single alternative and the disappearance of the others.[4]

An observer seeing one of the alternatives does not see the other ones. Subjectively, it does not differ from the picture where one of the alternatives is selected and the others disappear, i.e., from the state reduction picture. However, now, in view of Everett's interpretation, one has to conclude that the *state reduction is just an illusion appearing in the observer's consciousness*; in other words, it is a specific feature of the consciousness.

7. Extended Everett Concept (EEC)

Let us now move to the Extended Everett Concept (EEC) which allows one to consider quantum measurement at yet a higher level and leads to a number of very interesting consequences [3, 13–16]. The step that takes us beyond Everett's concept is to identify consciousness with the separation of the alternatives. Let us explain this.

Let us start from Everett's concept in the formulation used in Section 6: all alternatives exist (there is no reduction) but consciousness separates them. By thinking a little deeper, one can see that, in fact, the two central notions of this formulation are not defined and cannot be defined at present. Using the notion of 'separating the alternatives', we actually do not fully understand what it means and have to accept just a vague intuitive idea of its meaning. Similarly, while operating the notion of 'consciousness', we do not actually understand what consciousness is. Physicists cannot explain the separation of alternatives in the framework of quantum mechanics (and, hence, cannot fully clarify this notion), nor can psychologists, physiologists, and philosophers, who

[4] One should not think that in this way one of the alternatives is singled out, namely, the one seen by the observer. He observes (his consciousness perceives) all the alternatives, but he sees them separately.

actively work on the problem of consciousness inwardness, solve this problem. Apparently, the phenomenon of consciousness is somehow related to the work of the brain, but it cannot be fully explained by the brain functioning. It is rather the other way round, the processes happening in the consciousness (subjective feelings) direct and coordinate the work of the brain.

The Extended Everett Concept suggests identification of these two poorly defined notions, the 'consciousness' and the 'separation of alternatives'. It is assumed that *consciousness is identified as the separation of alternatives*. After this identification, first, there remains just one notion instead of two and, second, this notion can now be illustrated from two viewpoints: the physical one, and the psychological one. The separation of alternatives, not very clear in physics, is illustrated by what we know about consciousness, while consciousness, which is not very clear in psychology, gets illustrated due to what physics knows about the separation of alternatives.

In fact, one cannot expect more than that. In any science, initial notions stay vague until it becomes clear how these notions work and how all other notions arising in the theory are related to each other. By making the notion *consciousness* $\equiv$ *separation of alternatives* common to quantum physics and psychology, we take a step towards its more exact definition. Of no less importance (and maybe even more convincing) is the fact that combining these two notions leads to the explanation of some phenomena that are well known but up to now not explained. We will speak about this later.

Both Everett's interpretation and the EEC give, on the one hand, a description of the quantum world represented by a superposition of alternatives and, on the other hand, a description of the same world as perceived by the consciousness. This is the same quantum world but with separated alternatives. Alternatives constitute different 'projections' of the quantum world. If evolution is described in the framework of quantum mechanics, all these projections are essential and are only present altogether (as a superposition). In the description of the picture existing in the consciousness, the alternatives are separated, and each of them has a meaning but the sum is meaningless. Everett says: consciousness separates the alternatives. But in the framework of the EEC we say it slightly differently: it is the separation of alternatives that is consciousness.

At first sight, this identification seems to change nothing essential in the measurement picture. But this is not so. Now, after identifying consciousness with the separation of alternatives, one can pose the following question, which in fact does not relate to physics any more but is outside of its scope: *what happens when consciousness is turned off*? Indeed, states of turned-off or dimmed consciousness are known, these being *sleep, trance, meditation*, or what Young called the *unconsciousness*. What happens in transferring to such states from the viewpoint of the concept we consider?

Physics cannot answer this question but if we assume that separation of alternatives is identified as consciousness, then the answer is possible. Under this identification, turning off consciousness means turning off the separation of alternatives. It is logical to conclude: when consciousness becomes dimmed, *the separation of alternatives becomes incomplete*, 'partitions' between alternatives become transparent (Fig. 7). Immediately, an important conclusion follows: if consciousness is dimmed or weakened, then, while perceiving some

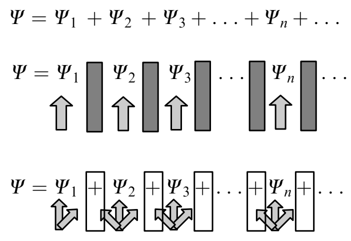

Figure 7. If consciousness and separation of the alternatives are identified, then dimmed consciousness (in particular, in the state of sleep or trance) means an incomplete separation of alternatives, in which consciousness looks into 'other alternatives' and can single out the most favorable ones among them.

alternative, it at the same time scans the neighboring alternative, and not only the neighboring one. Hence, a subject in the state of dimmed consciousness, perceiving some classical alternative, can at the same time *look into 'other alternatives'*.

To this must be added the assumption that a subject observing some alternative (while separating them) *can modify the probability of observing one alternative or another in the nearest future*. In the framework of the EEC, this assumption becomes natural because separation of alternatives, after identifying it with consciousness, can be considered in two ways: as a specific description of what happens in the quantum world, and as a mental phenomenon. The quantum world is based on objective laws but mentality is subjective; it is controlled, at least partly, by the subject. Therefore, it is natural to define *two probability distributions in the set of alternatives*: the objective one (regulating the choice of an alternative in the world of abiotic physical systems), and the subjective one (defining which alternative will be chosen by the subject). This question is discussed in more detail in Refs [3, 13–16].

The assumptions of the EEC are quite counter-intuitive and not typical for physics. However, analysis shows that the logical structure of the theory is simpler under these assumptions than in the Copenhagen interpretation or in Everett's interpretation in its original form. But most important is that with these assumptions we become able to explain many things that we face every day but that have had no explanations up to now.

For instance, the *free will*. What is free will? A person wants to leave the room and leaves it, or she wants to stay there and stays. She wants to get up from a chair and gets up, or stays seated if she wants. It seems simple but do we understand how it happens? How is the decision made? We will not find the answer by analyzing the work of the brain. The command to muscles comes from the brain but how is one of several alternative commands chosen by the neuron that first makes this choice? Physiology cannot explain this. The assumptions adopted in the EEC explain this in a natural way: all alternative behavior scenarios are present as superposition components but the subject can compare them with each other and increase the observation probabilities for the alternatives that seem more attractive to her (for instance, those more favorable for life).[5]

[5] Of course, if only the phenomenon of free will is considered and the postulates of the EEC are used only for its explanation, then these postulates seem quite voluntary. However, since they originate from a reasoning that starts from quantum physics, the whole construction becomes plausible.

In addition to the free will, this reasoning can explain such a strange fact as the *absolute necessity of sleep*. Everyone is so used to the phenomenon of sleep that we never think about this fact. But biologists and physicians cannot explain why sleep is *absolutely* necessary, why a person deprived of sleep for three weeks will certainly die. The answer that sleep gives rest to the organism does not actually explain this absolute necessity. The extended Everett concept explains this phenomenon: a person deprived of sleep has no opportunity to look into 'other alternatives' and choose the best one, leading to maintaining health and survival.

Beside these two, there are other fundamental phenomena that find natural explanations in the framework of EEC. Among them, for instance, there is the instantaneous and uncontrollable 'creative spark' leading to a discovery. There are also phenomena, probably existing in reality, consisting in observing events that naturally occur only with extremely small probabilities ('probability miracles').

8. The Extended Everett Concept: relations among "the three problems"

If one accepts the Extended Everett Concept, i.e., identifies consciousness with the separation of alternatives, then the relations between "the three great problems" are again slightly modified, and in this case they become especially diverse. These relations are represented in Fig. 8.

(1) According to the EEC, there is a field where only 'pure' quantum theory operates. In this theory, evolution is always described by a linear law (for instance, the Schrödinger equation) and is reversible. This quantum theory is correct for the description of abiotic matter. The reversible quantum world is represented by the world of abiotic matter. No notion of measurement is necessary in this world: measurement is only the interaction of the system with its environment, and all interactions in the reversible quantum world are correctly described by the usual linear quantum-mechanical equations. (It was this description of measurement that was discussed in Section 5 in connection with a decoherence phenomenon.)

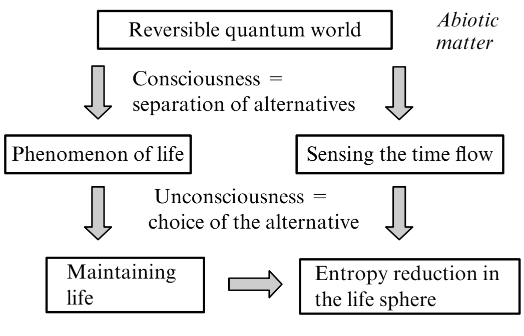

Figure 8. In the framework of the extended Everett concept, the relationships between "the three great problems" become deeper.

In the framework of the EEC, one can only speak of measurement in connection with the notion of the observer and, most important, the observer's consciousness. Thus, quantum theory gains the notion of consciousness, and hence the *phenomenon of life* (the upper arrow in the left-hand part of Fig. 8). As a result, the theory gains new opportunities which allow one to explain important and so far unexplained features of this phenomenon. Let us briefly dwell on this subject; for details, one can see Refs [3, 13 – 16].

First of all, the existence of consciousness, or separation of alternatives, enables one to explain the phenomenon of life. The key role here is played by the *classical nature of the alternatives*. By identifying the separation of alternatives with consciousness, i.e., with some attribute of living matter, the EEC explains the classical nature of the alternatives, which cannot be explained otherwise. Indeed, separation of alternatives is consciousness, i.e., an attribute of living matter. Therefore, it is legitimate to pose the question: to what components the quantum state of the world will be separated, and what will be the alternatives (the superposition components) *in the interests of life*?

The answer is obvious: the alternatives should be classical (quasiclassical), so that consciousness (in the regime of separation of the alternatives) perceives the picture of a locally predictable world (i.e., such a world in which the evolution of some spatial domain cannot substantially depend on the states of remote domains). If, instead of classical alternatives, essentially nonclassical ones were used (involving the features of quantum nonlocality), then each such alternative would give a picture of an unpredictable world in which the strategy of survival could not be worked out. Only classical alternatives provide the predictability of the world sensed subjectively, and hence ensure the very possibility of life.

Further, if one takes into account that consciousness can be in the 'boundary state', in which it is almost completely turned off, i.e., the alternatives are not completely separated, it becomes possible to explain *how life is maintained and the health of a living creature is preserved*. Here, the main role is played by sleep, during which the dimmed consciousness penetrates into 'other realities', the subject compares alternatives and is enabled to choose the one that is most favorable for life and health. Sleep is absolutely necessary for life namely due to the fact that it helps to choose the strategy for survival. Maintaining life is impossible without sleep.[6]

(2) The second line of relations between "the three great problems" connects the problem of measurement and the problem of the time arrow. Considering consciousness, or separation of alternatives, we necessarily come to the conclusion that the picture created by the consciousness contains something that is absent in the quantum world. The quantum world was reversible, while *consciousness creates the sensing of time flow* and the distinction between the present, past, and future (upper arrow in the right-hand part of Fig. 8). The present is distinguished by the fact that at this moment the subject is choosing the alternative that will be in the nearest future perceived by his consciousness. In the quantum world of abiotic matter, which evolves according to the Schrödinger equation, the notions of 'present', 'past', and 'future' are simply absent.

(3) As one of the aspects of the picture appearing in consciousness, the time flow singles out the time arrow. With respect to this time arrow, entropy increases. However, entropy decreases in the sphere occupied by life (living matter develops and becomes self-organized). This is also explained in the framework of the EEC.

[6] The phenomenon of sleep (periodically turning off clear consciousness and getting into a state of 'unconsciousness') exists not only for humans but also for animals whose physiology is close to that of humans. For more simple organisms, 'consciousness', i.e., the ability to perceive the surrounding world, is probably similar to what is called 'unconscious' for a human; hence, the phenomenon of sleep is of no significance to them.

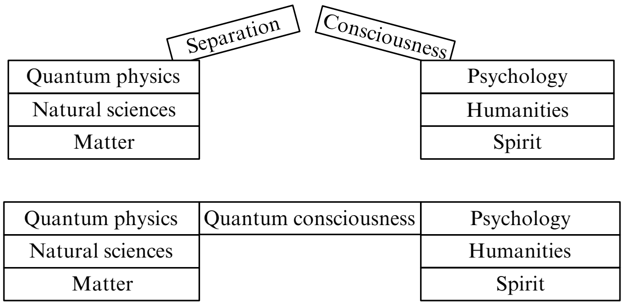

Figure 9. Identification of consciousness with the separation of alternatives generates the new notion of quantum consciousness, which is a general subject of study and, hence, the bridge between the natural sciences and humanities, between matter and spirit.

Briefly, this is because consciousness (in the boundary state) perceives various alternatives, analyzes them, and modifies the probabilities, preferring the ones that are more favorable for life. The last of these means that a subject perceiving some alternative is more probable to perceive, in the following instant of time, one of the alternatives that are most favorable for him. The special 'choice' of alternatives providing survival means that the *dynamics of life observed by consciousness are determined not by the cause but by the goal*. And this, of course, means a decrease in entropy in the life sphere.

(4) Identification of consciousness with the separation of alternatives actually generates a new notion of *quantum* consciousness, which has a unique property. Consciousness understood this way enters, as a necessary element, both quantum physics and psychology. This way, direct contact between these two sciences is established. Continuing this analysis, we see that quantum consciousness forms the bridge between the natural sciences and the sphere of the humanities (including nonscientific forms like religion). Eventually, one can say that quantum consciousness builds the *bridge between matter and spirit* (Fig. 9).

This is indeed a *bridge over a chasm*. There are many important relations between the material and spiritual spheres. However, quantum consciousness apparently makes a more solid contact between them: each of these spheres *needs* the other one for the sake of being conceptually closed.

9. Conclusions

The following conclusions can be drawn from above analysis.

(1) The question of what happens during measurement should be answered in the framework of physics as follows. In any case, reduction does not occur; what proceeds is the entanglement of the measured system with its environment and, as a consequence, the measured system decoherence. This is derived strictly in the framework of quantum mechanics. From a somewhat broader viewpoint, the answer to the same question is: during measurement, the observer's consciousness perceives the measurement result, which is equivalent to separating the alternatives.

(2) The question of what life is from the viewpoint of physics should be answered in the following way. Since consciousness is identified with the separation of alternatives, 'quantum consciousness', namely, the concept of consciousness resulting from this analysis, erects a bridge between physics and life. Life cannot be explained by only physical processes which obey the laws of physics. At the same time, one cannot say that no relation exists between the phenomenon of life and the laws of physics. This relation exists and it is important, but it is not a direct relation. From the Extended Everett Concept, it follows that the 'quantum consciousness' throws a bridge between (quantum) physics and life. Physics cannot do without such an important notion as consciousness (the most important component of the phenomenon of life), while life cannot be explained without invoking quantum physics.

(3) And, finally, the last question is: where does irreversibility come from? Based on the Extended Everett Concept, we come to the conclusion that the objective (quantum) world is reversible, while irreversibility arises in the picture of this world created by consciousness. Consciousness builds its life in a picture of the world where the time arrow exists, there is a qualitative difference between past, present, and future, and the future is 'locally predictable'. This is, of course, not accidental, since a survival strategy is only possible in such a world, namely, the very existence of life. This possibility is realized by increasing the probability of the subject observing favorable alternatives and means an entropy reduction in the sphere of life.

10. Appendix: Discussion

***Question* (*Al'tshuler B L*):** The talk creates a nostalgic feeling. Indeed, in 1947, *Literaturnaya Gazeta* [the Literature Newspaper] published a large article where Vitalii Lazarevich Ginzburg was accused of 'blatant idealism'. As to my question, it is: just before this talk, Valerii Anatol'evich Rubakov spoke about the anthropic principle and the multiplicity of worlds; he said that there can be infinitely many worlds. Is this multiplicity of worlds in the framework of the anthropic principle related to the multiplicity of Everett's worlds?

***Mensky*:** This relation was not discussed in the talk by Rubakov but it suggests itself. It also exists in the original Everett interpretation but even more so in the Extended Everett Concept. It is assumed in the EEC that consciousness can choose alternatives that are most favorable for life (more precisely, increase the probability that the consciousness perceives one of the favorable alternatives). This can be called the active version of the anthropic principle. But I would also like to touch upon the first part of Boris Al'tshuler's comment. Indeed, 'the ages meet' here. Our scientific community is too conservative (much more conservative than the scientific community abroad). In the late 1940s, one could be cursed here for quantum mechanics. Now, no one is cursed for quantum mechanics. But for the things like those I was speaking about, one is still cursed.

***Question*:** Some time ago we listened to talks about the irreversible expansion of the Universe. Does this irreversible expansion of the Universe occur only in our consciousness?

***Mensky*:** I think one should not absolutize what has been said and mix physics with philosophy. To be strictly logical, all alternatives, according to Everett's interpretation, are equally real, and the fact that consciousness perceives only one of them (for instance, the irreversibly expanding Universe) is the property of both the consciousness and the world scanned by this consciousness. In reality, all we see is a picture created in our consciousness. We see a single alternative but there are other alternatives as well, and they are no less real because we see just a single one. Also, recall what was just said about the anthropic principle and its relation to Everett's concept. Among all alternative pictures of the Universe there are some that principally cannot be observed by the human consciousness, since protein-type life cannot exist in such universes.

***Question* (*Maksimov E G*):** You spoke of 'quantumness' all the time. But there is a simple toy, called the Sinai billiard, that demonstrates, with a very simple model, how irreversibility appears. We can watch this toy, turn our heads away from it, fall asleep, or wake up, but this toy will still demonstrate to us the simple appearance of irreversibility.

***Mensky*:** Exactly. In this case, irreversibility arises regardless of whether the observer watches the system or not, for the simple reason that the Sinai billiard is a classical system. This is a system that also creates irreversibility, but for a different reason, which has absolutely no relation to what I have been speaking about. I only spoke about irreversibility in quantum systems. There, irreversibility appears only when these systems are subject to measurement (observation).

***Question* (*Maksimov*):** But in the Sinai billiard, the same irreversibility arises without any quantum measurement.

***Mensky*:** No, not the same one. In the Sinai billiard, irreversibility is of a completely different origin. In quantum mechanics, irreversibility appears because of decoherence (caused by the interaction with the environment), while in a classical system decoherence is assumed *a priori*, quantum coherence is absent in principle. In this case, irreversibility can appear as a result of completely different mechanisms. In particular, irreversibility in a classical system can arise due to the instability with respect to initial conditions. It is namely this case in the Sinai billiard. Classical equations that describe the evolution of the Sinai billiard are reversible, but irreversibility appears because this evolution is not stable with respect to initial conditions. The origin of irreversibility does not always have a quantum nature. In my talk, I only spoke of the irreversibility that appears in quantum mechanics, where it should apparently be absent due to the reversibility of the Schrödinger equation.

***Question*:** Could you please tell us how the ideas you just presented relate to the ideas and works of the Brussels school of Ilya Prigogine? For they, generally speaking, were interested in the same questions, including the time arrow, self-organization, and so on.

***Mensky*:** Indeed, many people have been interested in these questions, and different researchers have studied these questions from different viewpoints. One of the approaches was developed by the Brussels school. In fact, it is not so easy to compare different approaches. In my presentation, I specially did not dwell on comparing various approaches but chose a single line of reasoning. Even a single line cannot be traced in detail, more time is necessary. As to a comparison with Prigogine's approach, there are common points and there are distinctions.

***Question*:** You are speaking about some reduced entropy of living matter in comparison with inanimate matter. But the entropy of living matter is not lower than the entropy of inanimate matter.

***Mensky*:** I am not saying that the entropy of living matter is lower. I am saying that entropy can decrease in living matter instead of increase, which seems to me obvious.

***Question*:** This is not so obvious. As we know, Blumenfeld has shown that, in general, the entropy of living matter is not reduced. As he writes (and he has shown this in a physical way, so that it cannot be disproved), the entropy of a stone is the same as the entropy of a living organism.

***Mensky*:** If living matter is simply considered as matter, as a collection of atoms, it will behave like any other matter: all the usual physical laws are valid for it. But if we consider it from another viewpoint, like a living organism and not a collection of atoms, then the situation is changed, in particular, for the entropy. We see, for instance, that living creatures were once protozoa and then became more complex. In this sense, entropy does decrease in the sphere of life.

***Question*:** But also in this sense, it does not seem to work, because all chemical reactions that lead to the creation of living matter or to its complexification produce some additional substances as by-products.

***Mensky*:** Well, correct, correct.

***Question*:** They do not go only in this straight direction.

***Mensky*:** Exactly.

***Question*:** And, therefore, we do not arrive at any entropy paradox.

***Mensky*:** That is the point. Certainly, the entropy of the total system is increased, as it should be, but the entropy excess is ejected from the life sphere somewhere, namely, to a sphere without life. But in the sphere of life, the entropy is reduced. Of course, the processes occurring in living creatures do not contradict physical laws. It is not the violation of laws that happens in the life sphere, but something different. In the life sphere, the notion of a goal appears, which has no meaning for abiotic matter. It is only the cause that exists for abiotic matter, while the notion of a goal appears in the sphere of life. The goal is survival. And for achieving this goal, some (unfavorable) scenarios are rejected; more precisely, the probability of their perception by consciousness is reduced. This is what leads to entropy reduction in the picture seen by the consciousness. The payoff for it is the ejection of excessive entropy out of the sphere of life. This is one of the reasons why a living system is always an open system.

***Question*:** Could you please tell us, does this mean that the laws of nature changed with the appearance of life?

***Mensky*:** First, physical laws act regardless of whether life exists or not. Life differs only in the way how probabilities work. Only things allowed by physical laws occur, but in the picture observed by the consciousness of a living creature, some events favorable for life become possible, which are not probable from the viewpoint of physics. Besides, we still do not know anything about the origin of life. And I am not posing this question and cannot answer it. It is possible that life has always existed. Don't you assume this? I am just saying that the world looks completely different if we take into account the existence of living matter and living creatures. And the existence of living creatures, the laws of their existence do not reduce to physical laws, something new appears (although there is no direct contradiction with the laws of physics). This new thing is what I conventionally call 'consciousness', although consciousness should be understood here in an extended way. This notion is somewhat different from what is usually understood by 'consciousness'.

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