psychology Jean Piaget based his concept of logical-algebraic structures of intellect on the idea of implicative links and dependences in the consciousness. According to him, "none of the concepts expressing physical causality... are applicable to the understanding of linkages in the realm of consciousness" (see Ref. [7], p. 19). Thus, even though it is a long way from the problem of quantum measurement to the problem of consciousness, the problem of quantum measurement uncovers a new and uncommon aspect of links and dependences in Nature, whose properties resemble the properties of consciousness and whose existence in Nature is prerequisite for the emergence of consciousness. However, the clarification of all these circumstances is a task for the future.

5. Conclusions

The main idea of quantum mechanics, whether in the form of the Planck constant or in the noncommutativity of certain observables, must be brought to the recognition of relativeness and nonuniversality of the abstract concept of set (manifold) in the description of quantum systems.

This entails the necessarily probabilistic description of quantum systems: since a quantum system ultimately cannot be decomposed into elements or sets, we have to describe it in terms of probabilities of only a relative selection of certain elements or sets in its structure. This gives rise to the potential possibilities of quantum systems in an actual physical situation and the corresponding probabilities are ontologically real, like any other physically verifiable relationships.

In this way, the quantum potential possibilities (and probabilities as their measure) are no less objectively real than the conventional reality which we identify with the physically directly verifiable elements, particles, etc. As observed by Albert Einstein, "a field for a modern physicist is as real as the chair on which he is sitting".

This remark wholly applies to the quantum field described by the nonfactorizable wave function — that is, to the distribution of probabilities related to the pure quantum state. Indeed, this distribution of probabilities is as objectively real and hard to the touch as chairs, walls and all other hard-to-the-touch physical things.

These probabilities, however, presented in the pure quantum state, have another remarkable property that cannot be imagined in the world of chairs or other macroscopic objects: in the pure quantum state the probabilities of selection of elements from the ultimately detailed state of the system are mutually coordinated and correlated by the phenomenon of wholeness of the system, and form an implicative logical structure governed by this phenomenon of wholeness.

This idea of implicative logical organization of the probabilistic structure of quantum system in the so-called pure (non-detailable) state, and the governing role of the phenomenon of wholeness (in the redistribution of probabilities depending on the nature of development of the real experiment) is in good agreement with the results of quantum correlation experiments (for example, the experiments of A Aspect, N Gisin, and others).

References

1. Kochôn S "A new interpretation of quantum mechanics", in *Symposium of the Foundations of Modern Physics: 50 Years of the Einstein – Podolsky – Rosen Gedankenexperiment* (Singapore: World Scientific,1985) p. 151
2. Pfleegor R L, Mandel L *J. Opt. Soc. Am.* **58** 946 (1968)
3. Grib A A *Usp. Fiz. Nauk* **142** 619 (1984) [*Sov. Phys. Usp.* **27** 284 (1984)]
4. Pastur L A *Matematicheskaya Skhema Kvantovoĭ Mekhaniki* (Mathematical Scheme of Quantum Mechanics) (Kharkov: Kharkov State University, 1985)
5. Menskiĭ M B *Usp. Fiz. Nauk* **170** 631 (2000) [*Phys. Usp.* **43** 585 (2000)]
6. Von Neumann J *Mathematical Foundations of Quantum Mechanics* (Princeton, N.Y.: Princeton Univ. Press, 1955) [Translated into Russian (Moscow: Nauka, 1964)]
7. Piaget J *Izbrannye Psikhologicheskie Trudy* (Selected Psychological Works) (Moscow: Prosveshchenie, 1969)

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Quantum measurement: decoherence and consciousness

M B Menskiĭ

The letters to the editor received in response to my article in *Usp. Fiz. Nauk* [1] and published in this issue differ in content and purpose. In addition to comments on my article, their authors also present their own proposals for the development of quantum theory. Let the reader make his own judgment about the value of these proposals. In this note I will only answer the comments in my address made in three of these letters. These comments touch upon issues that are difficult in themselves, or were presented in my article too briefly. I hope that additional light will be thrown on the complicated issues raised in my article. To maintain the high level of the discussion, I will excuse myself from responding to remarks made in the other letters — in my opinion, they are addressed quite clearly in the article itself.

Article [1] is split into two parts, which are completely different with regard to the nature of the subject. The first (bigger) part is concerned with the particulars of the entangled states of quantum system and the related phenomenon of decoherence. The theory of decoherence explains how quantum measurement takes place. It resolves the paradoxes of quantum mechanics if we confine the treatment to open systems and do not attempt to find the mechanism of selection of one of the possible alternative results of measurement. This is quite sufficient for answering all the questions that can be reasonably asked within the framework of physics. From the standpoint of a physicist the question of selection is ill-posed or unnecessary, and any real system is open — it is only the entire Universe that is absolutely closed.

In the second part of the article we discuss the conceptual problems that arise when we go beyond the subject (methodology) of physics and look into the mechanism of selection. At this deeper level of analysis the paradoxicality of quantum mechanics remains, and the description of quantum measurement is not possible without explicitly including the consciousness of the observer in the consideration. To resolve the problem of selection at this level, we propose to identify two concepts: (1) the selection of the alternative quantum measurement, and (2) comprehension of the result of measurement by the observer.

M B Menskiĭ P N Lebedev Physics Institute, Russian Academy of Sciences
Leninskiĭ prosp. 53, 117924 Moscow, Russian Federation
E-mail: mensky@sci.lebedev.ru

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As ought to be expected, the most interesting questions and critical remarks are related to the second part of the article, devoted to selection and consciousness. Shortly (in paragraph 2) I shall address these questions. I would like to start, however, with a misunderstanding that comes up in one of the letters in connection with the theory of decoherence. This will also clarify certain principles that failed to receive proper attention in article [1].

1. A I Lipkin [2] criticises article [1] for allegedly being based on von Neumann's reduction postulate. In the beginning he writes:

"The fundamental, seminal and axiomatic concept for the theory going back to von Neumann and adopted by M B Menskiĭ is the postulate of the 'reduction of wave function' associated with the measurement in quantum mechanics".

This is certainly not the case. For those concepts of quantum measurement that are discussed in my paper (the phenomenon of decoherence and Everett worlds), the postulate of reduction is neither fundamental nor even necessary. By contrast, these concepts, and first of all the concept of decoherence, free us from the need to postulate the reduction of the state (collapse of the wave function). This is why they were proposed in the first place.

Lipkin attempts to eliminate the postulate of reduction on the grounds of a rather strange (to put it mildly) assertion: "the ENTIRE measuring component, complete with the procedure of comparison with the standard, CANNOT IN PRINCIPLE be included in the theory. We hold that the procedure of measurement contains a certain part (comparison with the standard) **that cannot be described within the framework of that chapter of physics in which it is used.** In all likelihood, an even more stringent statement is true: the procedure of comparison with the standard cannot be completely covered by any branch of physics). A similar feature applies to the preparation procedures" (capitals and boldface from the original).

This outlandish thesis and other formal constructions of Lipkin's, like his 'core of division of science', do not throw any new light on the issue of reduction (collapse). In fact, this is not necessary, because the theory of decoherence gives a clear physical analysis of this issue.

The theory of decoherence and, in particular, its discussion in my article, illustrates how the entirely conventional quantum mechanical analysis of the measured system, interacting with its environment (the instrument or measuring medium), leads to the same predictions as those which can be obtained using the reduction postulate. It is not necessary to assume that the reduction (collapse) of the wave function actually takes place. Decoherence explains why the reduction postulate leads to correct predictions even though in reality there is no reduction as such.

The key concept here is the concept of the entangled state. Article [1] does not present the entire theory of decoherence - we only describe its main idea and cite references containing a more detailed treatment. For more details the reader should refer to this literature. In particular, the relationship between the reduction postulate and decoherence is discussed in detail in Refs [3] and [4] (the first of these is cited in Lipkin's letter but seems to be misunderstood as well).

Although the theory of decoherence gives a physical explanation of something that is phenomenologically described by reduction, the reduction postulate does not lose its meaning but only changes its status. Reduction offers a simple and elegant method for calculating the behavior of the system after the measurement when the result of the measurement is known. In particular, the reduction pattern is useful for calculating the results of two or more consecutive measurements.

In this way, it is possible to describe quantum measurement at different levels: the reduction postulate gives the phenomenological description, the theory of decoherence gives a more profound 'microphysical' description. There is a deeper level of description of quantum measurement, which goes beyond the methodology of physics and involves consciousness. We shall speak of it below. One of the purposes of article [1] and book [4] is to show that the different approaches to quantum measurement, which are sometimes viewed as incompatible, are actually just different levels of description, each being correct if used in the right way.

In addition to the reduction postulate, there are other methods of calculation of the results of repeated measurement. For example, instead of using the reduction of state (collapse of the wave function) after each measurement, one can get correct predictions by calculating the correlation between the results of different measurements. This approach is analyzed in the work of D N Klyshko [5], quoted by Lipkin in his letter.

2. Now let us go to the more difficult issue of the role of consciousness in the theory of quantum measurements. This question is raised in the letter of A D Panov [6].

The role of consciousness was discussed in many works of many authors, starting with von Neumann. To the literature cited previously in Ref. [1] we should add the paper by Dieter Zeh [7], which offers a good review and a conceptual analysis of the problem. Observe that the discussion of this issue in Ref. [1] is by no means complete, and only expresses the personal opinion of the author.

In connection with Panov's letter we must first of all note a certain confusion of terms. In my article [1] I used the term 'consciousness' to refer to the known phenomenon from psychology, which apparently is a function of the brain. Occasionally I used the word 'comprehension' ('becoming aware of') to emphasize that this is a phenomenon, a process. In Panov's usage, 'consciousness' refers to a material object that supports this process. I would call this (whether it is the brain or some structures in the brain) the 'carrier of consciousness'. In article [1] we did not directly consider the carrier of consciousness, so the analysis proposed by Panov is a useful supplement to the article. Panov describes the decoherence of the material carrier of consciousness that takes place simultaneously with the decoherence of the measured system. This is useful for understanding what goes on in the case of quantum measurement. And even though Panov seems to disagree with article [1], his analysis actually supports and illustrates our conclusions.

Denoting by S, D, M, and E the measured system, the measuring device (detector), the carrier of consciousness (mind) and the environment (reservoir) respectively, Panov considers the unitary evolution which results from interaction between these objects and leads to the following change in the state of the total system:

$$\big(\alpha|S_\alpha\rangle + \beta|S_\beta\rangle\big)|D_0\rangle|M_0\rangle|E_0\rangle \rightarrow \alpha|S_\alpha\rangle|D_\alpha\rangle|M_\alpha\rangle|E_\alpha\rangle + \beta|S_\beta\rangle|D_\beta\rangle|M_\beta\rangle|E_\beta\rangle\,. \quad (1)$$

This differs from the treatment in article [1] only in that the degrees of freedom M are selected, interpreted as the carrier of consciousness. In exactly the same way as in Ref. [1], it is easy to show that although the final state of the total system after the interaction remains pure, the state of each subsystem becomes mixed — decoherence takes place. So the state of the measured system is now described by the (reduced) density matrix

$$\rho_S = |\alpha|^2 |S_\alpha\rangle\langle S_\alpha| + |\beta|^2 |S_\beta\rangle\langle S_\beta| \,. \qquad (2)$$

This formula is equivalent to Eqn (5) in [1] and describes the decoherence of the measured system S. Panov also inquires about the state of the carrier of consciousness M after the interaction. It is described by the density matrix reduced to the subsystem M:

$$\rho_M = |\alpha|^2 |M_\alpha\rangle\langle M_\alpha| + |\beta|^2 |M_\beta\rangle\langle M_\beta| \,. \qquad (3)$$

This means that the carrier of consciousness occurs (with corresponding probabilities) either in the state $|M_\alpha\rangle$, or in the state $|M_\beta\rangle$, but not in a superposition of these states. Accordingly, the process of interaction of all these objects leads to decoherence of not only the measured system S, but also the carrier of consciousness M.

Observe that the density matrix ρ_M of the form (3) can be obtained under assumptions less stringent than those used by Panov. In the presence of a macroscopic environment (reservoir) E, the density matrix ρ_M always has the form (3) by virtue of the orthogonality of the states $|E_\alpha\rangle$ and $|E_\beta\rangle$. If the states of the detector $|D_\alpha\rangle$ and $|D_\beta\rangle$ are orthogonal to each other, this will ensure the form (3) for matrix ρ_M, which will be true even in the absence of a macroscopic environment.

More important is the following remark. Panov assumes that formula (3) resolves the problem of selection by consciousness of one of the alternative results of measurement. He writes: "Just as in statistical mechanics there is no problem of selection of one of the classical states (p, q) for the state defined by the distribution $\rho(p, q)$, here we have no problem of selection of the state of consciousness".

In fact, the problem of selection of alternative is not resolved by formula (3). The analogy with statistical mechanics drawn by Panov demonstrates only that a physicist usually does not encounter this problem at all. If the alternatives are enumerated, and each has its associated probability, then nothing else is needed to answer any question put forward by a physicist. This is what I meant when claiming that in the framework of the theory of decoherence of open systems (whose states are described by density matrices) there are no paradoxes or logical difficulties, and the resulting theory may be considered quite adequate as long as we remain on the level of treatment, which is characteristic of physics.

The problem arises only if we feel it necessary not only to enumerate the alternatives with their respective probabilities, but also to describe the mechanism of selection of one of these alternatives. This means that we are asking questions not usually asked by physicists — that is, we move onto the level of metaphysics. At this deeper level of analysis the density matrix of the form (3) does not satisfy us any longer. This density matrix describes the decoherence of the carrier of consciousness and does not solve the problem of selection any better than the density matrix (2), which (in a different notation) was discussed in article [1] and which describes the decoherence of the measured system.

In order to resolve the problem of selection we need to take a more radical step. Different authors do it in different ways, but the most interesting solutions (in my opinion) are based on the many-worlds interpretation of quantum mechanics proposed by Everett. According to Everett, all the alternative results of quantum measurement are realized, but they are realized in different worlds. These worlds are perfectly identical, with the only difference that this particular measurement leads in different worlds to different results (of course, each subsequent measurement splits each of the worlds again). In each world there is an observer (or observers), and the difference between observers in different worlds is that they see different results of measurements.

Now it seems that the problem of selection of the result of measurement is no longer there, because all alternatives (all Everett worlds) are equally real. From our experience we know, however, that in the consciousness of any particular observer the measurement gives one particular result. So in the description of the consciousness (psyche) of one particular observer we need to put only one result of measurement — the result that is registered by this observer. So the selection of one out of all possible alternatives is still necessary. The problem of selection does not disappear, it only moves from the domain of physics to the domain of psychology (the theory of consciousness of individual observer), or, more precisely, to the domain of metaphysics (because the problem arising in psychology is rooted in quantum physics).

Can we now solve the problem of selection that has become a subjective one? Is it possible to explain how the selection of an alternative is made in the consciousness of the individual observer — or, in other words, the selection of the Everett world in which the observer finds himself.

Obviously, the answer will depend on what we mean by 'explaining'. In some cases explanation is the rapprochement of concepts that before the explanation seemed to be remote. One thing is explained in terms of another. In article [1] we proposed *to identify the concept of selection, arising in quantum physics, with the phenomenon known in psychology as comprehension*. So when asked what is selection, we answer comprehension. Selection (of the alternative result of measurement) occurs when this particular observer comprehends in which of the Everett worlds he finds himself. And inversely, to the question 'what is comprehension' (that is, the transition from the state when something is not comprehended to the state when it is comprehended) we propose to answer it is the selection of one out of many alternative Everett worlds.

Of course, something like this is always said in connection with Everett worlds. Something like this was said by Everett himself, and by all his followers. In article [1] we attempted to simplify the formulation as much as possible, remove all extras, and emphasize the main point. In place of the formula "The consciousness of the observer selects one of the alternatives" we propose the statement "The consciousness (comprehension) is the selection of the alternative". It is possible that some authors meant exactly this, although I did not come across any formulations that would unambiguously express this idea.

For example, I Z Tsekhmistro [8] writes in connection with my proposed solution of the problem of selection: "This path, however, has already been walked by von Neumann in his much more elegant and shrewd analysis, when he demonstrated that a consistent analysis of the problem of measurement inevitably leads to consciousness (to the act of comprehension of the reading of the instrument) as the last authority responsible for the reduction of the wave function.'' However, when we open the cited book by von Neumann, we see that he only states that it is necessary to explicitly include the consciousness of the observer in the consideration, and nothing more. This necessity was stated by many authors after von Neumann, which I duly noted in my article. This, however, is a statement of the problem but not its solution. I have not encountered a solution based on identifying the consciousness and the selection.

To repeat once again: it is quite reasonable to hold the viewpoint that this problem does not exist at all. Tsekhmistro writes further:

``Let us emphasize the major difference between the views of von Neumann and M B Menskiĭ. Von Neumann obviously accepts the standard Copenhagen interpretation of quantum mechanics with its initial and correct (as proved by the entire evolution of quantum theory) idea of primacy of probabilities. Therefore, he does not have the question posed by M B Menskiĭ '(1) how is one of the alternatives selected in quantum measurement'. The answer is obvious — at random.''

But of course! Such a question does not arise in the framework of physics. A physicist will be quite content with the probabilistic predictions, and random selection of an alternative is self-evident. We have to repeat again: the question of the *mechanism* of selection of alternative only arises on the metaphysical level of treatment. No one is obliged to consider the problem on this level. The conventional physical treatment is quite sufficient for all practical purposes. The resulting theory is logically closed, it can be checked experimentally and is verified perfectly well.

To many the transition to the metaphysical level and to additional questions might seem just an unnecessary game, and this standpoint is quite reasonable and even advantageous in many respects. What I tried to say in the second part of my article was formulated very cautiously: if for some reason or other (perhaps just out of curiosity or by way of intellectual exercise) we go over to metaphysical level and begin asking 'nonphysical' questions, then one of these questions will be concerned with the mechanism of selection of an alternative, and one of the possible answers (elegant in my opinion) consists in identifying the consciousness and the selection.

Of course, such a solution of the problem of selection is purely verbal, and for a physicist may be of no value at all. Verbal solutions, however, are typical for metaphysics. In our case the solution seems to be elegant because it brings together two difficult conceptual problems from entirely different branches of science: (1) what is selection in quantum physics, and (2) what is the concept or phenomenon of consciousness in psychology. We get an explanation (or description) of a difficult psychological concept in physical terms, and vice versa.

Apart from all else, such a statement of the problem is very favorable for the hypothesis of the existence of active consciousness capable of changing the probabilities of different alternatives for a particular observer. This hypothesis is discussed (at a very preliminary level) in article [1], but here we are not going to touch upon it. We shall only note that this hypothesis is correct only if the number of Everett worlds is infinite (this remark was included in the English translation of article [1]).

Going back to the question of reduction (collapse) of the wave function, we have to conclude that, similarly to the theory of decoherence, Everett's quantum mechanics does not assume that the collapse actually takes place. After all, collapse or reduction means that all alternatives vanish except one. But in Everett's quantum mechanics all alternatives remain equally real, only they exist in different worlds. And only in the consciousness of each individual observer is there an illusion that only one of these worlds exist — that is, only one alternative. There is no collapse at all, but to an individual observer it seems to take place.

By the way, this is what makes the concept of collapse so useful for practical calculations. For a particular observer there is only the one Everett world in which he finds himself. And in this world only one alternative is realized. He can safely ignore the fact the other alternatives are realized in other worlds (inhabited by his counterparts). Accordingly, he may assume that at the time of measurement the collapse takes place that leaves only one alternative. Calculations based on this assumption will give a correct answer for the Everett world in which this observer lives.

3. At the end of Panov's letter [6] the status of quantum theory that resolves the problem of measurement with the concept of decoherence is discussed. Panov agrees with the conclusion made in article [1] that no logical difficulties will arise in the quantum theory of open systems if the phenomenon of decoherence caused by the environment is taken into account phenomenologically. He believes, however, that such a theory ``may cause some discontent because, along with the Schrödinger equation, the theory also involves some phenomenology, which is as important as the dynamic laws themselves. This phenomenology is fundamental in the sense that it has to be considered not derivable from to any other principle (unlike, for example, thermodynamics, which can be derived from statistical physics).''

This remark is quite reasonable. We can reply, however, that there is at least one method of phenomenological description of decoherence that has the required properties. It is the phenomenology of continuous quantum measurements (that is, continuous decoherence), based on restricted path integrals, or, which is equivalent, on complex Hamiltonians [3, 4]. It is fundamental by construction.

This phenomenology is not derived from anywhere, and actually constitutes a part of quantum mechanics. This becomes obvious if we use a formulation of quantum mechanics in terms of Feynman's path integrals. Then the evolution of a closed system is described by the integral along all possible paths, whereas integration for an open continuously measured system must be restricted to a certain subset of paths. Namely, one should only include those paths that are consistent with the information obtained in the course of measurement (and 'recorded' in the environment). As a result, both closed and open systems are described by the Schrödinger equation, but in the case of an open system the Hamiltonian contains an imaginary part [3, 4].

Another proof of the fundamentality of such phenomenology is the fact that it emphasizes the dynamic role of information: the effect of the environment of a certain subsystem on its dynamics only depends on what information about the subsystem remains in the environment. All these issues are discussed in detail in book [4].

So, Panov quite reasonably notes that the phenomenology in the theory of open systems must be fundamental in nature. However, the theory of restricted path integrals is essentially fundamental, and provides a good basis for an adequate theory of open systems.

References

1. Menskiĭ M B *Usp. Fiz. Nauk* **170** 631 (2000) [*Phys. Usp.* **43** 585 (2000)]
2. Lipkin A I *Usp. Fiz. Nauk* **171** 437 (2001) [*Phys. Usp.* **44** 417 (2001)]
3. Mensky M B *Usp. Fiz. Nauk* **168** 1017 (1998) [*Phys. Usp.* **41** 923 (1998)]
4. Mensky M B *Quantum Measurements and Decoherence. Models and Phenomenology* (Dordrecht: Kluwer Acad. Publ., 2000)
5. Klyshko D N *Usp. Fiz. Nauk* **168** 975 (1998) [*Phys. Usp.* **41** 885 (1998)]
6. Panov A D *Usp. Fiz. Nauk* **171** 447 (2001) [*Phys. Usp.* **44** 427 (2001)]
7. Zeh H D *Found. Phys. Lett.* **13** 221 (2000)
8. Tsekhmistro I Z *Usp. Fiz. Nauk* **171** 452 (2001) [*Phys. Usp.* **44** 432 (2001)]