

LETTERS TO THE EDITORS

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Readers comments on "Quantum mechanics: new experiments, new applications, new formulations" by M B Menskiĭ

From the Editors. Today in the world literature, as at certain times in the past, are issues actively debated related to the interpretation and, more generally, to the foundations of quantum theory. At the same time these issues do not receive adequate treatment in the Russian-language physical publications. For this reason, *Usp. Fiz. Nauk* recently published a review by M B Menskiĭ entitled "Quantum mechanics: new experiments, new applications, new formulations of old problems" (*Usp. Fiz. Nauk* **170** (6) 631 (2000) [*Phys. Usp.* **43** 585 (2000)]). The editorial preface to this paper invited the readers to make their contributions to the discussion of the foundations of quantum theory. Some letters have been received and are presented below. Wishing to ensure free expression, we did not subject these letters to peer review, and take no responsibility for their content. We believe that such an approach is more or less justified by the current situation.

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Does the phenomenon of 'reduction of the wave function' exist in measurements in quantum mechanics?

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This letter is in response to review [1]. My purpose is to point out a fundamentally different theory not mentioned in Ref. [1]. This theory rejects the phenomenon of 'reduction (collapse) of the wave function' (introduced by John von Neumann and Paul Dirac in the 1930s), and the closely related 'quantum theory of measurement', the unconditional existence of which is taken in Ref. [1] for the basis, as unjustified and not validated experimentally. I am referring first of all to the well-known works of D N Klyshko [2, 3]. The same view is shared by the author of this letter [4, 5]. This view was presented in our large joint paper entitled "On the 'collapse of the wave function', 'quantum theory of measurements', and the 'incomprehensibility' of quantum mechanics" [6], where we propose a clear-cut formulation of nonrelativistic quantum mechanics, free from the concept of 'reduction (collapse) of the wave function'. This letter is based on the ideas of Ref. [6] (see Sections 3.1, 3.3, 4) [1].

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1. Analysis of the main points

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 the wave function' associated with measurement in quantum mechanics.

One of the most common illustrations of the 'reduction of wave function' is the following. Assume that we are measuring some variable — for example, the position of particle in the plane of the screen (photographic plate), and this variable corresponds to an operator B. The reading of the instrument is b_1. According to most textbooks and the vast majority of theoretical physicists, this implies that:

Statement 1: this measurement is the phenomenon that is to be described by quantum theory;

Statement 2: it is proclaimed that in the language of quantum theory this phenomenon is described as the instantaneous reduction of the wave function (WF) of the system from $\Psi = \sum_k c_k |b_k\rangle$ (in the general form in Dirac's notation) to $|b_1\rangle$ with the probability $|c_1|^2$ (according to Born's rules). This jump is known as the 'reduction' or 'collapse' of the WF;

Statement 3: it is proclaimed that this transition is not described by the Schrödinger equation — that is, it is 'illegal' as far as the equations of standard quantum mechanics are concerned.

The incompleteness of contemporary quantum mechanics, which follows from this last statement (based on the preceding two), and the resulting need for an extension of its foundations, are what has been understood since the times of von Neumann as the '**problem**' of 'reduction (collapse) of the wave function'.

[1] The main ideas of this comment to Ref. [1] were discussed with the late D N Klyshko directly after the presentation by M B Menskiĭ of his theory at V L Ginzburg's "All-Moscow seminar on theoretical physics" (23 February 2000).

From the time of its formulation in the early 1930s, this problem has been regarded as a very serious one, and the attempts to resolve it went as far as introducing the consciousness [7, 8] or a multitude of worlds (Everett's many-worlds interpretation [9, 10]) into quantum mechanics. This problem is also central for the so-called 'quantum theory of measurements'.

Observe that the direct observation of a bright dot on the photographic plate on the one hand (in different tests the dot will occur at different locations of the front of the plane wave, but if the beam of particles is sufficiently weak, not more than one dot will form in each test run), and the 'phenomenon' of '*collapse* (or *reduction*) of wave function' on the other, are not one and the same thing. The former is an *empirical fact*, whereas the latter is only one possible *interpretation* of this fact, based on the theoretical assumptions 1 – 3 above.

Let us analyze these statements and see how well founded they are.

Doubts start with the **first statement**. For instance, V A Fok (in his polemics with Bohr) maintains that three stages must be distinguished in the structure of real experiment in quantum mechanics: "**preparation** of the object (P), the behavior of the object under fixed external conditions, which is what is described by the quantum mechanical **theory** (T), and the **measurement** itself (M)" (see Ref. [11], p.166) [2]. We can represent this three-way structure by the formula

P	T	M

A similar entirety (rather than just its theoretical component) termed "the nucleus of branch of science" is the object of analysis in Refs [4 – 6].

The boundary between these elements is flexible: one can enhance the theoretical part by including some of the measurement component (this is the domain of the theory of measurements), but 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 branch 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. This property of the extreme terms in the structural formula P – T – M we call 'non-theoreticality'. We cannot offer a rigorous proof of this statement, like the proof of Gödel's theorem in arithmetic, but there are a number of arguments in its favor.

Observe first of all that all this discussion and all these arguments can also be applied to classical mechanics. Then the analog of the contended view will be the requirement to include the experimenter with the yardstick measuring the distance traveled by a body sliding down an inclined plane into Newton's equations of motion. This requirement (like '**Statement 1**' above) is doubtless only from the Laplacian standpoint, which holds that "everything, including man, consists of atoms, and atoms are described by mechanics, therefore everything, including the acts and thoughts of man, can be described by the laws of mechanics". This philosophical rather than physical reason cannot be refuted by any argument except that in our times the ideology of such mechanical extremism is not commonly accepted. For example, the system approach holds the opposite: that a system possesses properties that cannot be reduced to the properties of its individual elements. Therefore, the reduction of all phenomena to mechanical features (whether classical Laplacian or quantum, like Schrödinger with his cat) is not absolutely necessary. This, however, is a purely philosophical issue that is discussed in greater detail in Refs [4, 5].

[2] A similar articulation was mentioned by W Heisenberg (see Ref. [12], p. 20), and H Margenau [13]; however, the interpretation is different.

This critique of **Statement 1** already casts doubt on the validity of **Statement 2**. However, we shall subject to scrutiny other foundations of this statement as well.

Two snags in the formulation of **Statement 2** were obvious from the start. First, it is clear that the measurement can be carried out in such a way that it destroys not only the state but also the system itself (for example, the registration of quantum particles with photodetector). Because of this, Wolfgang Pauli introduced the distinction between measurements of the first kind (nondestructive) and the second kind (such that destroy the state or the system), and restricted the validity of **Statement 2** only to the measurements of the first kind.

Secondly, Born's postulates say nothing yet about the state of the system after the measurement. Accordingly, the main argument in favor of **Statement 2** is usually the thesis of von Neumann that if the system is subjected to two measurements (of the first kind) that follow one another immediately, then the result of the second will be the same as that of the first. Von Neumann referred to the known Compton – Simon experiment [14] on the collision of photons and electrons. This experiment has since been regarded as an empirical validation of **Statement 2**. But is this interpretation correct?

A correct statement of the problem for **repeated measurement** in a Wilson chamber in the framework of standard quantum mechanics based on the Schrödinger equation was treated by L Schiff as the problem of calculation of a distribution of probabilities of excitation of two atoms by a passing fast quantum particle (electron). The calculation gives a tangible probability only when the path of the particle is nearly parallel to both the line drawn between the atoms and the direction of the final momentum of the scattered particle. In other words, the experimental results, usually cited in support of von Neumann's thesis and **Statement 2**, can be described by the conventional quantum mechanics without **Statement 2**. It seems that today, all known experiments can be quantitatively described by the standard algorithms of quantum theory and Born's postulate. Therefore, **Statement 2** and the consequent **Statement 3** are also unfounded.

In real quantum mechanics, **Statement 3** is replaced by an acceptance of the fact that the Schrödinger equation (or its analog), which describes the linkage between states (of the change of states) in quantum mechanics, must be supplemented by Born's rules of 'probability interpretation of the wave function' (PIWF), which link together the mathematical representation of a state of the system (the wave function) and the corresponding measurements, and have nothing to do with the change of states. Such is the structure of quantum mechanics. Classical mechanics is constructed in a similar way: the states are described by the equation of motion, while the procedure of measurement (comparison with the standard) fixes a particular state.

This view of the problem is based on a particular interpretation of *state* in quantum mechanics. According to the definition given in Refs [4, 5], the state of a physical system is something that, if known, gives answers to all questions regarding this physical system in that particular branch of physics. Accordingly, since we assume that all questions that can be asked in quantum mechanics should refer not to the readings of measurements, but rather to the distribution of probabilities of different measurables whose definition requires a long series of measurements, the reading of an individual measurement cannot be identified with the state of the system (if only it has not been obtained in an eigenstate) *either before or after* the *act of measurement*. This statement seems quite stringent, because it is more customary to associate the state with the definite values of measurables. This statement, however, is completely consistent both with Born's postulates and with other postulates of quantum mechanics [6].

In this way, we come to the conclusion proclaimed by D N Klyshko and maintained by the author, which states that the 'problem of reduction of WF' is just a hypothesis (or postulate) proposed by Dirac and von Neumann (1932), and is a typical example of a 'vicious circle' — first one is asked to take for granted that the WF for some unknown reason is destroyed outside of the region of registration (for measurements like determination of the position of the particle), and then this is promoted to the rank of a natural law (as they say, 'adopted by repetition'). Nevertheless, the reduction in some textbooks and monographs is listed among the fundamental postulates of quantum mechanics (see, for example, Ref. [16]), although its necessity is questioned by other authors (see Refs [17–21]). As a matter of fact, Dirac's projection postulate (used for describing the reduction of WF) is not needed, and is never used for the quantitative description of actually observed effects [6].

2. Myths [3] of quantum measurement

The ultimate purpose of the 'quantum theory of measurements', as it is understood in Refs [1, 16, 17], is the theoretical (quantum mechanical) description of the process of measurement, which is inseparably linked (or even coincident) with the 'phenomenon' of reduction (collapse) of the wave function and **Statements 1–3** analyzed above. Accordingly, the above analysis also applies to the 'quantum theory of measurements', and in our opinion the very statement of such a global purpose is wrong.

What then is the subject of the 'quantum theory of measurements'? Out of various effects of the measuring device upon the measured system we select the following: (1) destruction (in measurements of the second kind); (2) filtering; (3) interaction through the test object in indirect measurements.

It is the different versions of indirect measurements that are the main area of concern for the quantum theory of measurements. In other words, the proper domain of the quantum theory of measurements is the theoretical analysis of the interaction between the measured system and the 'test object' in the case of a nondestructive measurement of the first kind in the framework of standard quantum mechanics. In this case the system is extended through the inclusion of the appropriate part of the measuring device (the test object, or, which is essentially the same, some part of the measuring system). This is equivalent to the **displacement of the boundary T–M** in the P–T–M structure described above. This gives rise to the quantum mechanical problem of such a composite system, which is solved by the standard methods using the Schrödinger equation or its analogs. This is a normal well-posed quantum mechanical problem. Its solution, however, is often supplemented by the assumption of the 'reduction of the WF' on the grounds discussed earlier. In other words, a jump is introduced in the end without any theoretical justification. Therefore, to the theory of measurements as such one should assign whatever happens before this jump — which does not go beyond the limits of the standard quantum mechanics (into which we also include quantum statistical mechanics, where the role of the wave function is played by the density matrix).

A similar situation is observed with the effects of **filtering**. One should make a distinction between filtering (for example, with a pinhole or polaroid) and measurement, where a filter is often a component of the measuring device. *Filters prepare a state*, but to measure something one also needs a *detector* (by detection we mean some real evidence of the existence of particle, like a click in a Geiger counter or a track in a Wilson chamber). Filtering is aimed *directly at the states*, at the controllable modification of the states, whereas the acts of measurement are directed at the values of measurables whose probability distributions describe the state of the system. When the boundary T–M or P–T is displaced, filtering is included into the theory. Sometimes it is described in a consistent quantum mechanical manner, like in the Stern–Gerlach experiment, but more often the approach is less consistent (as a matter of fact, quasi-classical), using the appropriate projection operator in a mathematical layer. The latter is sometimes done rather tacitly. For example, in the experiment described in Ref. [2] a fast particle with a given momentum is registered by two Geiger counters separated by some distance. In the theoretical treatment of this experiment the problem is reduced to the description of the interaction of this particle with the atoms of the counters — that is, to the inelastic scattering of the particle on a pair of atoms, rather similar to the problem with the Wilson chamber mentioned earlier. The difference is that this time the atoms are 'fixed' by the Geiger counters, whose size acts as the spatial filter for the states of atoms on which inelastic scattering with the particle takes place.

The 'problem of reduction' does not arise in any of these cases, like in the case with the test object.

So we see that the initial GLOBAL statement of the 'problem of quantum theory of measurements', closely related to the 'problem of reduction of the wave function', is not correct, being based on 'Statements 1–3', which are ill-founded. The proper theory of measurements is related to the quantum mechanical treatment of various possibilities of indirect measurements, and involves about the same scope of issues as the classical theory of measurements. In both theories that part of the measurement procedure which is formulated as a physical problem is solved within the domain of the corresponding branch of physics. The procedure of measurement, however, also includes the comparison with the standard, which in principle is a technical rather than a physical or psycho-mental (that is, involving the consciousness) phenomenon.

In this way, the nonrelativistic quantum mechanics today is quite convincingly described by the standard formalism of quantum mechanics and supported by experiments. There are

[3] By myths we refer to statements that are adopted without sufficient grounds and cannot in principle be proved experimentally.

no experimental or theoretical grounds for revision of the foundations of nonrelativistic quantum mechanics. In particular, the 70-year old attempt to include the 'phenomenon of consciousness' into the foundations of quantum mechanics (the tradition dating back to von Neumann [7] and supported today by such serious scholars as E Wigner [24], R Penrose [8], M B Menskiĭ in Russia [1], and others) is hardly justified. "We must always divide the world into two parts — the observed system and the observer" — claimed von Neumann. — The fact that this division may be drawn arbitrarily deep inside the organism of the actual observer constitutes the principle of psychophysical parallelism [4]. This division, however, needs to be drawn somewhere... Because the experiment can only lead to statements like 'the observer has experienced a certain (subjective) sensation', but never like 'this physical variable has a certain value" (see Ref. [7], p. 308). This statement of von Neumann combines the philosophy of physicalism (in the Laplacian sense), instrumentalism, and neopositivism (logical positivism), very popular in the 1930 – 40s. With the demise of neopositivism (which was scattered to the winds by the post-positivists in the 1960 – 70s; see Ref. [5] for more details), the role of the observer as the solution of the problem of measurement (reduction of WF) was transferred to the consciousness [1, 25, 16]. Consciousness, like 'deus ex machina' resolving the difficulties of a plot in the plays of 17th and 18th centuries, is expected to cut short this 'psychophysical' infinity (anything can be ascribed to God or consciousness). The above analysis demonstrates the shabbiness of such constructions.

The same can be said of the many-worlds interpretation [9, 10] that appeared in 1970s and assumed that each term in $\Psi = \sum_k c_k |b_k\rangle$ "corresponds to a separate world. In each world there is its own quantum system and its own observer, and the state of the system is correlated with the state of the observer. The process of measurement may be viewed as the process of branching of the wave function, or the process of 'splitting' of worlds". In each of the parallel worlds the measured quantity B has a certain value b_i, and it is this value that is seen by the observer that "settles down in his world. Because of this, the effective reduction of the wave packet takes place for the observation in each of the parallel worlds" (see Ref. [10], p.25). The presentation of this theory always mentions only one observer, and for a reason: the case of more than one observer can hardly be resolved within the framework of this schizoid (from Greek 'to split') conception.

A similar situation is observed with the so-called 'quantum teleportation', dealing with triple correlations. "The interpretation of this effect, adopted in Refs [26 – 33], like its name, is based on the popular concept of the instantaneous reduction (collapse) of the wave function as a result of the measurement, leading to quantum nonlocality. Observe that this beautiful effect is also completely described by the quantitative quantum formalism" [2, 34].

As far as the concept of **decoherence** is concerned [1, 35], here we must note certain aspects.

1. In Refs [1, 35] decoherence is related to the problem of 'reduction of the wave function' in measurements in quantum mechanics. Since we believe that this problem does not exist, we leave this aspect out of consideration.

2. There is something that M B Menskiĭ classifies as mesosystems — systems consisting of a large number of atoms. When the number of atoms is very large, mesosystems become macrosystems. Essentially we are dealing here with the experimental verification of de Broglie's expression for the characteristic scale of quantum mechanical interference effects as the mass of the system increases. There is, however, no need to introduce any special effect of decoherence.

3. A special class of problems relates to the interaction between a quantum system and a thermostat (heat buffer). As a matter of fact, this is the domain where the theory of decoherence takes its beginning and is being developed.

Summarizing, we may conclude that Born's postulate gives the algorithm for comparison between theory and experiment. It is the main measurement-related postulate of quantum mechanics that is consistent with all known experiments. The concept of 'reduction of the WF', however, currently seems unnecessary.

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[4] According to von Neumann, the principle of psychophysical parallelism is 'fundamental for any natural philosophy'.

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Physical interpretation of quantum mechanics

R S Nakhmanson

The text that follows was written in response to the publication of paper by M B Menskiĭ [1] and the call from the editors of *Uspekhi Fizicheskikh Nauk* [*Physics – Uspekhi*] journal to continue an open discussion of the fundamental physical and philosophical problems of quantum mechanics in the form of "Letters to the Editors". These initial and boundary conditions have predetermined my polemic and summary presentation: in the first part I give critical comments on certain aspects of Menskiĭ's paper, and in the second part I present the fundamentals of the alternative interpretation of quantum mechanics (QM), referring for the details to the original publications.

1. Paper of M B Menskiĭ

In Section 2.1 of his paper Mensky shares the popular opinion that the experiment performed by Aspect's team [2] and concerned with verification of Bell's inequality [3] conclusively blocks the way for the local-realistic models. This, however, is not the case, and Aspect himself knew that. The new thing in Ref. [2] as compared with the experiments carried out in the preceding decade was the fast switching of conditions of registration of photons, which precluded the possibility of a relativistic informational linkage between the particles in the EPR pair. This gave rise to the legend of nonlocality of QM, of the 'instantaneously' correlated behavior of the EPR pair, even though its constituent particles may be hundreds of light-years apart. This, as justly noted in Ref. [1] and elsewhere, is contrary to our 'intuition', to the common sense shaped by our everyday experience — but, as they say, nothing can be done about that.

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Let us see, however, what Aspect writes at the end of his paper [2]: "The switching of the light is effected by acusto-optical interaction of the light with ultrasonic standing wave at 25 MHz, providing a commutation at 50 MHz, i.e. a change of orientation each 10 ns. This time is short compared to L/c (40 ns), but unfortunately it is not possible with these devices to achieve a random switching. In this respect, the experiment is far from the thought experiment".

Another *experimentum crucis* — the so-called 'delayed choice' — was carried out by Alley's team [4]. The special feature was that this team used a random commutation of a Pockels cell in one of the arms of the Mach – Zehnder interferometer.

What is the matter then, and why were Aspect and Alley so keen on randomness? They themselves did not dwell much on that. In 1993 at a conference at Olympia I said to Alley: "In a random sequence each term in the series is unpredictable. Is it that you suspected the ability of particles to predict the situation and wanted to prevent that?" "I guess you're right", — he replied.

To the best of my knowledge, the faculty of prediction was first expressly surmised in 1992 in Ref. [5]. Such a possibility is also assumed in a recent work of Zeilinger's team [6]. This idea leads on to consciousness and its linkage with matter, which is the subject of the latter half of Menskiĭ's paper. There is, however, an important distinction: explicitly in Ref. [5] and tacitly in Refs [2, 4, 6] it is assumed that matter itself is endowed with consciousness, whereas Menskiĭ, in the steps of von Neumann and Wigner, only considers human consciousness.

We shall return to this point later on, meanwhile just noting that if matter has the faculty of prediction, then Bell's theorem does not hold, the local-realistic models of microworld are feasible, and nonlocality is outcast. All this, including the intelligence of matter, can be reconciled with our intuition and common sense. If our ancient nature-worshiping ancestors or the little child of today could use our modern experimental equipment, they would not be surprised by the behavior of elementary particles.

In Section 3 Menskiĭ considers the problem of superposition of wave functions and its transformation upon transition to macroscopic systems ('Schrödinger's cat'). Unfortunately, he falls victim to the common mistake of going too far in identifying the mathematical construct (the wave function) with the material object, whether it is the elementary particle or the cat. Speaking of the space of states, he forgets that it is the space of wave functions rather than a real space, and that the superposition of functions does not imply the superposition of objects. Quoting from the beginning of Section 3:

"As known, the space of states of a quantum mechanical system is linear. This means that, along with any two of its states $|\psi_1\rangle$, $|\psi_2\rangle$, also possible is their linear combination (superposition) $c_1|\psi_1\rangle + c_2|\psi_2\rangle$ with arbitrary (complex) coefficients c_1, c_2. For example, if a point particle may occur at either of two points, it may also occur 'at both points at the same time'. There is nothing like that in classical mechanics. For example, a stone may occur either at one point, or at another, but not at both points at the same time".

This last observation of Menskiĭ is certainly correct, but he is wrong with respect to the elementary particle: no-one has so far observed one and the same particle at two points at the same time, and no-one is likely to do that in the future. Yes, the interference of amplitudes exists in the microworld, and