We can try to improve this model, announcing formally that the environment E is the entire remaining Universe. Then system U becomes closed, because the Universe has no 'greater environment'. This, however, is not possible for the following reason. If we assume that system E is the rest of the Universe, then system U is the entire Universe. It is well known, however, that for the exact quantum state of the Universe the concept of external time does not exist [4], and the evolution of the quantum state of Universe is not a unitary evolution in time. Hence, the unitary description of evolution of system U as time evolution becomes impossible as well.

One can imagine two ways (two programs) for overcoming this difficulty. One way (A) is the construction of a consistently quantum description of the Universe together with the explicit description of generation of internal phenomenological time, indication of the explicit method for describing the subsystems of the Universe, and indication of the method of linkage of these subsystems with the internal time — which amounts to the construction of the complete quantum cosmology. The other option (B) is the phenomenological inclusion of the entire Universe that is external to the composite quantum system U under consideration — using the spontaneous reduction of the wave function, or positive definite operators, or restricted path integral, or some other way. Option (A) seems to be the most consistent; today, however, it is not yet clear whether this program is feasible even in principle. Option (B), as noted by the learned author of Ref. [1], does not lead to logical quandaries or paradoxes. In our opinion, however, it 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 irreducible to any other principle (unlike, for example, thermodynamics, which can be derived from statistical physics). It should have been derivable from quantum cosmology, but option (B) leaves quantum cosmology far beyond the scope of the theory. The problem is further aggravated [and we see this as a logical stumbling block for program (B)] by the fact that such phenomenology can be introduced in different ways, and the equivalence of these ways has not been proved. In our opinion, the problem of quantum measurement essentially consists in the following dilemma: either the quantum theory of measurements is in fact quantum cosmology, or it involves an essential and not quite unambiguous phenomenology.

We have demonstrated that the dynamic description of selection of one alternative by the consciousness is possible within the framework of the unitary model described above. Although this model, as duly noted, is open to criticism, we believe that the feasibility of such a description is an indication that the consciousness of the observer should not be off handedly disregarded in the unitary quantum dynamics, and the principle of psychophysical parallelism on the quantum level cannot be written off.

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Theory of measurements and the collapse of the wave function

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Usp. Fiz. Nauk **170** (6) 631 (2000) [*Phys. Usp.* **43** 585 (2000)] carried an interesting paper by M B Menskiĭ who touches upon some issues related to the theory of measurement in quantum mechanics — in particular, the possible interpretation of the function of consciousness in terms of quantum measurements.

I appreciate the very fact of preparation and publication of this article as a very important and welcome event. As noted in the editor's preface to the paper by M B Menskiĭ (further on referred to as MBM for short), there has been almost no discussion of philosophical issues related to the theory of measurement in the Soviet (as well as in the Russian) scientific literature. This extreme pragmatism of the Soviet (and now Russian) school of theoretical physics, possibly induced by the many decades of ideological pressure, persists unfortunately to this day. Limitations on the freedom of thought always bears negative results. One illustration of this rule is the fact that the Russian theoretical guild (which has produced prominent schools of theoretical physics and mathematics) lags behind in the domain of ideology (algorithms etc.) of quantum computers. One may find some consolation only in the fact that we are somewhat better with applied ideas (for example, with the ideas how to design the 'hardware' for quantum computers).

Going back now to the content of the paper of MBM, I would like to touch upon certain issues on which I do not quite agree with MBM.

Essentially, this letter deals with the following. I present (quite concisely) my view of the theory of measurement (which is a verifiable hypothesis), which holds that quantum theory is a complete theory, and is capable (in principle) of giving a complete description of the interaction of 'quantum' objects with 'classical' ones, the 'reduction (collapse) of the wave packet', etc. The source of 'probability', inherent in quantum mechanics in the standard interpretation, is assumed to be the detector, which may be regarded as a reservoir with special properties (for details see below). In our treatment, it is the degrees of freedom of the reservoir that act as Bohm's hidden variables.

Thus, the selection of an alternative resulting from a quantum measurement is accomplished by the reservoir. As a matter of fact, we hold that the quantum probability is of the same nature as the classical probability associated, for example, with flipping a coin. In the classical case, the measure of the space of initial states leading to the coin landing on its edge is negligibly small; accordingly, in the quantum case this should correspond to the negligibly small

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measure of the initial states leading to a state of the type of 'Schrödinger's cat' — the superposition of macroscopically distinct states. Observe that Everett's many-worlds interpretation (supported by M B Menskiĭ), assumes the opposite — namely, that the initial states leading to superpositions of different macroscopic states, are typical. This assumption can be verified in the framework of the existing quantum theory by very concrete calculations using standard methods (see below). Such verification seems today quite feasible although technically not quite trivial, and this issue will hopefully be resolved in the near future. As a matter of fact, one of the purposes of this letter is to give a clear formulation of what quantities need to be calculated to come to a comprehensive and unambiguous settlement of the issue of measurements in quantum mechanics. Such formulations are proposed at the end of this letter; at this point I am going to share some considerations that go beyond the proper subject of physics and are related to the problems associated with any attempt to answer the technical question of the reduction of the wave function in the framework of the existing quantum theory.

Option 1. The collapse of the wave function is eventually proved.

If we assume that my assumption is good and proved, and the quantum theory is a complete and essentially deterministic theory, we come to the situation of a hundred years ago or earlier, when classical mechanics seemed to be a theoretically and experimentally established theory giving a quite adequate picture of the physical world. This brings us to the following question. If contemporary physics is in principle capable of describing the entire material world, including man and his nervous system, the genetic mechanism, etc., then man's psyche, 'free will' and all man's performance in general are a natural and unambiguous result of the unitary evolution of our metagalaxy with the initial conditions of the 'Big Bang', slightly corrected perhaps for the existence of black holes. This view will hardly find many advocates, and is certainly not shared by the author of this letter. How can one reconcile deterministic physics and, e.g., the subjective faculty of 'free will', and is this possible at all? The way out might consist in introducing some new phenomenon, which is not yet present in the quantum theory. Recall that oriental philosophy, in addition to concepts of Consciousness and Matter, also has the concept of Medium (Fohat), that is responsible for their interaction. (According to the theosophy of Madame Blavatsky, Fohat, the "dynamic energy of Cosmic Ideation", is "...the bridge by which Ideas existing in the Divine Thought are impressed on Cosmic Substance as the 'laws of Nature'." — *Translator's Note*). However transcendental this might be, there should exist some experimentally measurable effect — for example, an inherent slight decoherence. Ideas of this sort were discussed, for instance, by B B Kadomtsev, who introduced the concept of external noise as the source of decoherence. Roger Penrose in his book *Shadows of the Mind* (Oxford University Press, 1994) refers to such a presumed phenomenon as 'Factor X'. The opinion of the author of this letter differs from the views of these renowned physicists only in that the existence of such a phenomenon does not follow from the existing theory and is not necessary for resolving the issues of the theory of measurement [according to Assumption (1) above].

In any case, if such external noise does exist, it can be described quantitatively on the basis of experimental data. The practical construction of sufficiently large devices that undergo unitary evolution for a long enough time (quantum computers) will hopefully answer to what extent the evolution of a known and completely described (from the standpoint of contemporary physics) physical system can be unitary.

In all likelihood, the effect of 'external noise' is so weak that it will hardly be noticed against the background of the ordinary known causes of phase shift. The final answer, however, will be given by the experiment.

Option 2. Collapse of the wave function cannot be proved.

The selection of an alternative which arises as a result of quantum measurement is a key issue of concern for many physicists. Einstein was especially outspoken on this matter. If we assume that such a selection takes place in a purely mystical way, so that the mechanism of selection is not found in any other department of physics (which is how it seems to be in the standard interpretation), then it would be quite natural to believe (see MBM and R Penrose), that at this point physics naturally borders on issues that are beyond its scope — such as the question of the nature of consciousness. This would be exactly the case if the technical demonstration of the reduction of wave packet had not simply failed, but had proved the impossibility of this in the framework of the existing theory.

Nevertheless, without denying such a possibility in principle, we would like to note that this would be a rather strange situation if the main mechanism of such a phenomenon tacitly appears as the main and only reason for reduction of wave packets with an unpredictable outcome, but otherwise is not manifested in any way, does not render itself to quantitative measurement, etc. More reasonable would be a mechanism well described by physics — at least experimental physics (see above).

Let us now discuss in greater detail the problem of theoretical (technical) demonstration of the possible reduction of a wave packet. Observe first of all that if the reduction of a wave packet can be technically demonstrated as the result of unitary evolution of the system of particle + reservoir under the given state of the system, then the result is unique, because the selected alternative becomes obvious from the form of the final wave function. This problem, however, is not that simple. As a matter of fact, one has to determine the result of measurement as a function of the infinite number of variables describing the detector (the reservoir). It is rather obvious that it is only the infinite number of variables that is available, for example, in spatially unlimited reservoir with soft modes (like photons) that can provide for reduction of the wave packet. Because of this, numerical calculation can only give some indication of the trend (which is also quite helpful).

Another method would consist in the calculation of variables averaged over the state of the reservoir. Let us consider this option using the exemplary problem of a particle in a double-well potential linked with some kind of reservoir. This problem has been studied by many authors and turned out to be a good model for processes of decoherence in physical realizations of quantum bits (qubits). Being well studied, this model can help to resolve our issue of concern, since for certain conditions imposed on the reservoir it can serve as a model of a detector.

The analysis is usually concerned with the difference of probabilities of the particle occurring in the left-hand or right-hand pit $P(t) = P_{\mathrm{L}}(t) - P_{\mathrm{R}}(t)$, averaged over the state of the reservoir. The study of such a quantity alone, however, is not sufficient for our purposes. For example, it can vanish at infinity in different ways. One can imagine that, depending on the state of reservoir, we have either $P_{\mathrm{L}}(\infty) = 1$ or $P_{\mathrm{R}}(\infty) = 1$, as we have assumed. It is also possible however, that $P_{\mathrm{L(R)}}(\infty) = 1/2$, or that the probabilities obey some distribution function, and the end states are states of the type of Schrödinger's cat — that is, coherent superpositions of the 'right-hand' and 'left-hand' states. Therefore, it would be interesting to study, for example, the variable

$$M = P_{\mathrm{L}}(t) P_{\mathrm{R}}(t) , \tag{1}$$

averaged over the states of the reservoir. Such a quantity will vanish when and only when the states of the type of Schrödinger's cat are excluded (or the measure of such states normalized to the total measure vanishes).

Now let us give an additional and perhaps somewhat unexpected argument in favor of the assumption that it is the reservoir that answers for the outcome of measurement. If we assume that the outcome of measurement depends not only on the wave function of the particle, but also on the state of the reservoir, then it would be natural to expect that such an effect would reduce the precision of the rule of the 'square of the wave function', which would then be a law only in the idealized situation.

This is actually the case, and this phenomenon is known as flicker noise, sometimes also called $1/f$ noise according to the shape of its frequency spectrum. This noise appears in all nonequilibrium processes, and the process of consecutive preparation and subsequent detection of a large number of particles in one of the states is an example of a nonequilibrium process. The more or less commonly accepted explanation of flicker noise is the following. Any system, apart from the detected particles (for example, electrons in a conductor), also contains a large number of other degrees of freedom (phonons, photons, impurities) that interact with these particles. These degrees of freedom are responsible for such flickering, which also occurs on a very large time scale. As a result, the attempt to continue the measurement as long as possible in order to gain in accuracy fails, because the error of measurement accumulates with time as $\delta N \propto t$ (the time exponent will differ from one if the spectral density is other than $1/f$). Of course, not all degrees of freedom that contribute to flicker noise are important for the reduction of wave packet, but the degrees of freedom of the detector (or the reservoir responsible for the reduction of wave packet) will inevitably contribute to the noise.

Let us now discuss another difficult issue of the theory of measurements: the rate of reduction of wave packet. This problem is especially clear in the Einstein–Podolsky–Rosen (EPR) experiment. From the theoretical standpoint, a similar problem arises in the description of the conventional measurement of the position of one particle. Indeed, in this case, having registered the particle at one point, we can be sure that it will not be registered at other points — again we are dealing with the nonlocal change of the *a priori* probabilities. In both cases, if we assume that the time taken by the measurement is finite and does not depend on the form of wave packets, we have to accept that the reduction of wave packet (the localization of wave function) occurs faster than the speed of light. Generally speaking, this circumstance does not contradict the relativistic invariance, and does not provide for transmission of information faster than light (this has been discussed by many authors).

Nevertheless, in this issue as well it is necessary to demonstrate technically how it happens. By analogy with Eqn (1), we should analyze the two-time correlator

$$\langle P_{\mathrm{L}}(t) P_{\mathrm{R}}(t+\tau) \rangle . \tag{2}$$

Qualitatively, the reduction of the wave packet can be interpreted as a process of tunneling. Such an analogy is especially apt, for example, in the case of splitting of a wave packet falling through a one-dimensional conductor onto a junction with two others (Y-shape junction). Assume that the transmitted particle can be detected in one of the conductors by detectors located far from the junction. After registration by one of the detectors, a registration in the other arm can only occur as a fault. In the process of entanglement of the degrees of freedom of the first detector with the degrees of freedom of the particle, the wave packet located near the second detector ought to decrease in magnitude and probably lose its shape. Nevertheless, such deformation cannot lead to the literal pulling (movement) of this wave packet towards the first one — this would be contrary to the dynamics of propagation and the probabilities of detection calculated in the standard way. So we have to assume that we are dealing with a process like tunneling, whereby the wave packet (from the channel with the detector that did not fire) does not appear in any intermediate position, but simply disappears (over a finite time).

To end, let us emphasize the main theme of this letter. Many complicated issues in the theory of measurement in quantum mechanics can be translated from the level of speculations and credos to the level of concrete theoretical and experimental verification of assumptions, hypotheses and theories. The formulation of such verifiable hypotheses is a step forward, and some of them have been presented above.

In particular, we proposed that:

(a) the reservoir is the source of quantum mechanical probability, and there is a direct analogy between classical and quantum 'random' processes;

(b) the degrees of freedom of the detector act as 'hidden variables';

(c) flicker noise may be regarded as evidence of the definitive role of the reservoir for all types of noise, including the shot noise that is conventionally attributed (at low temperatures) to 'quantum mechanical stochasticity';

(d) quantum mechanics is local in the sense that all its fundamental laws are local, while the 'nonlocality' related to the faster-than-light reduction of wave packet is an effect (similar to tunneling) that follows from these local and Lorentz-invariant laws (equations);

(e) there must exist some experimentally detectable phenomenon (Penrose's X-factor, or Kadomtsev's external noise) that points to the inevitable nonunitarity of evolution of quantum system.

If these hypotheses (a)–(d) are true, then the existence of such phenomenon does not follow from the theory, and the only argument in favor of its existence is one's confidence that the Universe together with humankind is not a 'quantum computer' with a strictly predetermined behavior.