ABOUT SCHIZOPHRENIC EXPERIENCES OF THE NEUTRON OR WHY WE SHOULD BELIEVE IN MANY-WORLDS INTERPRETATION OF QUANTUM THEORY

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> The truth about physical objects *must* be strange. It may be unattainable, but if any philosopher believes that he has attained it, the fact that what he offers as the truth is strange ought not to be made a ground of objection to his opinion.
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> – Bertrand Russell *The Problems of Philosophy*

1. Introduction. The Many-Worlds Interpretation (MWI) introduced by Everett (1957) fascinated many physicists and philosophers. However, most papers about MWI ended with "but"; usually, even the advocates of Everett's idea saw different significant difficulties in MWI (see, for example, Clarke 1974). I believe that all these "buts" are either incorrect or insignificant. In fact, I consider MWI being *the best* available quantum theory.[1]

Shrödinger's equation (the basic equation of quantum theory) yields a very convincing explanation for the results of experiments performed on microscopic systems. It also yields the existence of many worlds. The addition of the collapse postulate, that represents the difference between MWI and the standard approach, is not motivated by and does not provide explanation for any experimental findings. Its sole purpose is to abolish the consequence of Shrödinger's equation regarding the existence of many worlds.

The "inertia" of thought makes accepting the dramatic change in our picture of reality that MWI requires very difficult. Physicists are not ready for this dramatic change of philosophical approach, while most philosophers do not know enough physics to see the necessity of this change. Historical parallel with Copernican system versus Ptolemaic and Tychonic nicely traced by Tipler (1986). Lewis (1986), however, advocates the thesis of existence of many worlds even without relying on any evidence from physics experiments.

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† I am grateful to the many friends and colleagues for their patience in the endless discussions which resulted in this paper, and especially to Ferdy Shoeman whose help made it possible to complete this project.

[1] Recently I learned that I do not belong to an absolute minority. Lockwood (1989) published a philosophical monograph putting forward many of the arguments in favor of MWI, while Davies (1980) and Wolf (1990) brought ideas of MWI to the general audience.

Today's technology does not allow us to test the existence of the "other" worlds. So only God (or "superman") can actually apply MWI. We, however, are in the position of God relative to a neutron. Today's technology allows us to test the existence of many "worlds" for the neutron. This is why I discuss neutrons, first. For purposes of exposition I attribute to the neutron the ability to feel, to remember, and to understand. But I want to emphasize that the validity of MWI does *not* depend on the existence of a sentient neutron.

The plan of this paper is as follows. In sections 2 and 3 I explain the design of neutron interferometer and show that a conscious neutron passing through the interferometer *must* have schizophrenic experiences. In section 4 I introduce neutron's MWI and explain how it solves the problem of neutron's schizophrenia. In section 5 I discuss neutron interferometer in the framework of the formalism of quantum theory, and show how identification of a neutron with a localized wave packet yields neutron's MWI. The problems of a preferred basis and interpretation of probability for neutron's MWI continue to be discussed in sections 6 and 7. In section 8 I give a quantum mechanical description of the observer in the neutron interference experiment. I show that the collapse of a quantum state which is a part of measuring procedure in the standard approach, is not necessary for explanation of the experiences of the observer. In section 9 I discuss experimental testing of MWI. In section 10 I present MWI of the Universe. Popular "buts" and misconceptions about MWI are discussed in sections 11-13. In section 14 I summarize arguments in favor of MWI. Section 15 devoted to the causal interpretation: the best quantum theory without collapse after MWI. In the last section I change the key, and discuss social behavior of a believer in MWI.

2. Neutron's beam splitter. Let me start with an analysis of a simple experiment performed many times in physics laboratories. A neutron is passing through a beam splitter S toward detectors D_1 and D_2, see Figure 1. The outcomes of this experiment, as reported by numerous experimentalists, are always as follows: *A* single neutron coming toward the beam splitter is detected *either* by detector D_1 *or* by detector D_2. A natural conclusion from these reports is that the neutron *either* takes trajectory SD_1 *or* takes trajectory SD_2 and, consequently the experimentalist sees only one triggered detector. There are two distinct possibilities and only one of them is realized.

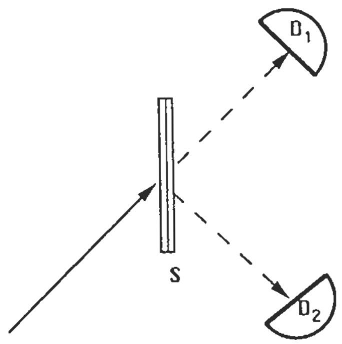

FIGURE 1

Before the experiment, we can imagine two different worlds corresponding to the two possible outcomes of the experiment. The two worlds differ with respect to the position of the neutron, the states of the detectors, the state of mind of the experimentalist, the record in the experimentalists's notebook etc.. In the standard approach only *one* of these worlds exists. According to MWI, however, both possibilities of the experiment are actualized. Both detectors D_1 and D_2 are triggered, the experimentalists sees both outcomes, writes down both results in the notebook, etc.. When an experimentalist reports to me that the neutron was detected by D_1, I, as a believer in MWI, *know* that there is also a world in which I got a report about a neutron detected by D_2, and that the other world is not less "actual" than the first one. This is what "many worlds" means. There are many worlds like the one we experience.

I will concede that based on the results of the experiment shown in Figure 1 it is natural to assume that there is only one world: *A neutron passing through a beam splitter either is scattered by a given angle or continues on the straight line without being disturbed.* The neutron has a single trajectory. We can bolster our confidence that this is the correct description by considering results of the experiments with a mirror and two beam splitters in the configurations shown in Figure 2. The prediction for the outcomes of these experiments is that half of the trials the neutron is not detected by either of the two detectors (when it takes the trajectory without the mirror), and the other half it detected at random by D_1 and D_2. The experimental results are, indeed, as predicted. However, when we combine these two systems, we discover that what was true for each of the system individually is not true anymore: the neutrons are not detected at random by D_1 and D_2. This combination of two beam splitters and two mirrors is called a *neutron interferometer* and I will discuss it in the next section.

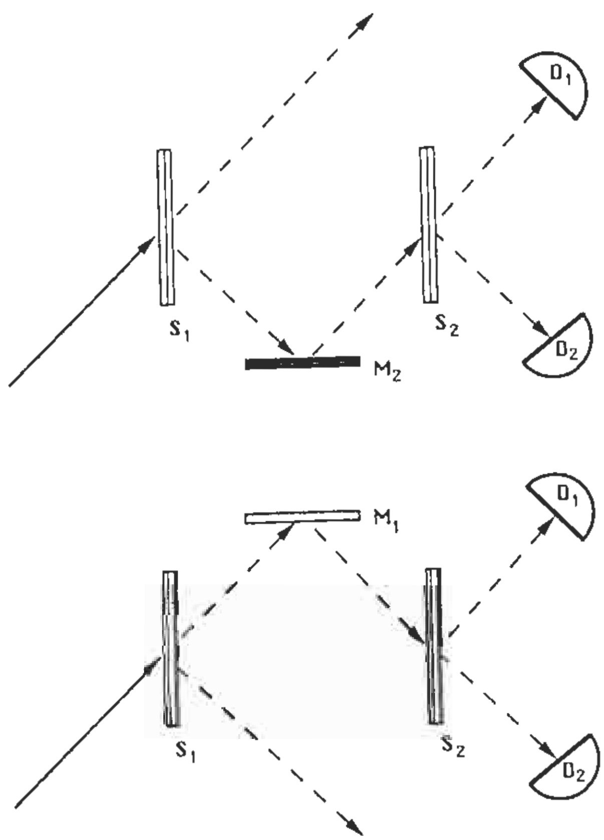

FIGURE 2

3. Neutron interferometer. The neutron interferometer is an experimental device that can be found in several laboratories in the world (for a review see Greenberger 1983). The assumption about the neutron passing through a beam splitter that I made in previous section cannot explain the results of the neutron interference experiment. These results, combined with the assumption that there is only one world for the neutron, compel the neutron to have schizophrenic experiences.

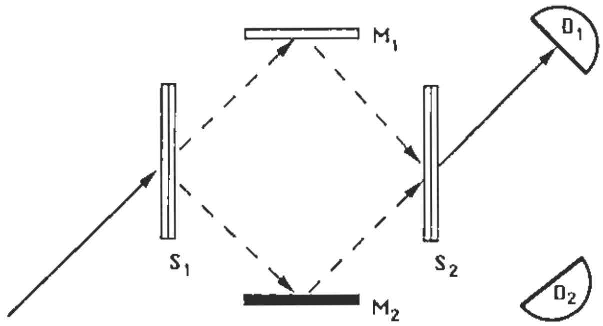

FIGURE 3

In Figure 3, a schematic neutron interference experimental setup is shown. It consists of a source of neutrons, a beam splitter S_1, two mirrors M_1 and M_2, another beam splitter S_2, and two detectors D_1 and D_2. Based on our understanding of the process of a neutron passing through a beam splitter, i.e that it either is scattered by a given angle or continues on the straight line without being disturbed, we can make a prediction for the results of this experiment. Each neutron takes one of the four trajectories $S_1M_1S_2D_1$, $S_1M_1S_2D_2$, $S_1M_2S_2D_1$, or $S_1M_2S_2D_2$. Therefore, the neutrons have to be detected at random by detectors D_1 and D_2. But the outcomes of the experiment are not what is expected! *All* the neutrons are detected by detector D_1.[2]

One can keep holding the idea that the neutron has a definite trajectory: either $S_1M_1S_2D_1$ or $S_1M_2S_2D_1$. Only the assumption of randomness with which the neutron chooses its way in the beam splitter S_2 has to be abandoned. However, this hypothesis is also refuted experimentally. Placing an absorption screen on the way of the neutron in front of M_1 or in front of M_2 should reduce the number of neutrons detected by D_1, but it clearly cannot cause the neutron to go toward D_2. The experimental results, nevertheless, are different: with the screen the neutrons are detected at random either by D_1 or by D_2.

We cannot explain the experimental results by the picture with a single trajectory for the neutron. We are compelled to admit that in some sense the single neutron passes through *two* separate trajectories: $S_1M_1S_2$ *and* $S_1M_2S_2$. If the neutron can feel, it experiences being in two places and moving in two different directions simultaneously. Inside the interferometer the neutron must have schizophrenic experiences. Suppose that the mirrors in the interferometer are made from different materials such that the neutron can distinguish between, say, a soft kick by mirror M_1 and a hard kick by mirror M_2. Even in this case, the neutron that passed through the interferometer has no answer to a simple question: "Which mirror kicked him?"

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[2] Here I sacrifice rigor for simplicity by omitting technical details. A precise statement is that one can tune the interferometer such that all neutrons are detected by D_1.

4. Two neutron worlds To avoid positing schizophrenic neutrons, I will state that during the time the neutron is inside the interferometer the world of the experimentalist encompasses *two* worlds of a neutron (two neutron worlds). In each of these two worlds, the neutron has a definite trajectory: $S_1M_1S_2$ for one and $S_1M_2S_2$ for the other. In each world there is a causal chain of events. For example, in one world the neutron passed through beam splitter S_1 undisturbed, went toward mirror M_1, was hit by the soft mirror, moved toward S_2, was scattered by the beam splitter toward detector D_1, and was absorbed by D_1. In each world the neutron has unambiguous answers to the questions: Where is the neutron now? What is the direction of its motion? Which mirror did it hit? Note that my assumption of two neutron worlds is useful even if there are no sentient neutrons. The assumption allows *me* to answer the above questions, while according to the standard approach these are illegitimate questions.

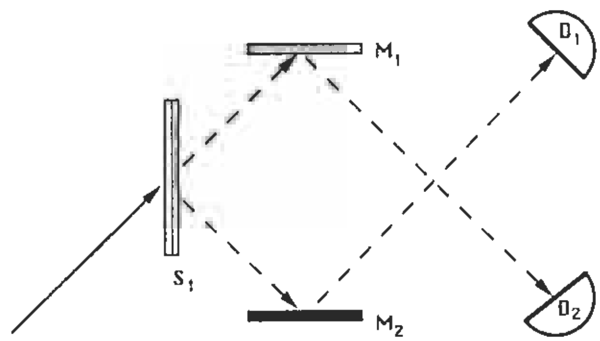

FIGURE 4

The neutron in one neutron world does not know (unless it has studied quantum mechanics and believes in MWI) about its "brother" in the other world. In the same way as most of us do not think that besides the world we know there are other worlds in the same place and at the same time. The experimentalist, however, is in the position of God for the neutron. He can devise an experiment to test whether the neutron of one world feels the neutron of the other world. To this end he modifies the neutron interference experiment by removing beam splitter S_2, see Figure 4. One neutron world corresponds to the trajectory $S_1M_1D_2$ and the other to the trajectory $S_1M_2D_1$. We know that in the original location of beam splitter S_2 the two neutrons meet each other. They are in the same place at the same time moving in different directions. Under normal circumstances (in a single world) two neutrons would scatter on each other. But the results of the experiment, as in Figure 4., shows no scattering whatsoever. The rate of detection of neutrons by D_1 (D_2) is *not* affected in any way when we eliminate the brother-neutrons by placing an absorption screen before mirror M_1 (M_2).

Let me discuss again the neutron interference experiment (Figure 3). The hypothesis of many (two in this case) worlds solved the problem of the neutron's schizophrenia inside the interferometer, but it seems that we left with the problem of schizophrenic *memories* of the neutron. The two worlds become one again in beam splitter S_2. What memory does the neutron have after it leaves S_2? Was it kicked by the soft mirror M_1 or by the hard one M_2? Quantum theory tells us that the neutron *cannot* have memories about which trajectory it passed (in which world it "lived"). Quantum mechanics does explain why the neutron passing through the interferometer is detected only by D_1, but this explanation relies on the fact that the neutron has no internal variable that "remembers" which trajectory the neutron has taken. The capability of the neutron to remember is not ruled out completely: it might remember its trajectory while it is inside the interferometer, but this memory has to be erased when the neutron leaves the second beam splitter. In fact, there is a physical realization of an experiment in which the neutron "remembers" inside the interferometer which path it takes. One of the devices that can serve as a beam splitter for a neutron is a particularly designed magnet (Stern-Gerlach apparatus). In this case, the path of the neutron is correlated with the value of an internal variable called spin. However, the second magnet, that replaces the second beam splitter, erases the correlation.

The neutron cannot "feel" objects from other worlds, it cannot remember that it "lived" in two worlds. So, is there any reason for the neutron to believe in the existence of the other worlds? It has the same reason as we do. It has no other way to explain why passing through the neutron interferometer it always ends up in detector D_1. However, as we will see next, the quantum theory (with many worlds) explains these experimental facts very nicely.

5. Quantum mechanical explanation. In quantum mechanics particles do not and *can not* have trajectories. Instead, a particle is described by a quantum state evolving in time. For the neutron, the quantum state is represented by a spin component and a spatial wave function. According to the standard interpretation, the square of the magnitude of the wave function gives the probability per unit volume of finding the particle in a given place. Frequently, the spatial wave function spreads out significantly and then there is no answer to the question: where is the particle? In fact, in any real situation there is no exact answer to this question. (Zero uncertainty in the position requires infinite energy.) Nevertheless, physicists frequently consider trajectories of particles. The discussion I presented before will not be rejected on these grounds. What physicists mean today when they say that the neutron passes on a given trajectory is that during all this time the spatial wave function of the neutron is a *localized wave packet* (LWP) whose center moves on this trajectory.[3] Inside the interferometer, however, the wave function of the neutron is not a LWP and, consequently, the neutron has no trajectory. The quantum theory shows that the wave function of the neutron, when it leaves the beam splitter S_2, is the LWP moving toward detector D_1. This is the explanation why the neutron is never detected by detector D_2. Let me demonstrate now this interference effect using some formulas.

I designate by $|up\rangle$ and $|down\rangle$ the states of the neutron moving 45° up and down accordingly (see Figures 1-4). Then, due to the passage through a beam splitter the state of the neutron changes as follows:

$$|up\rangle \rightarrow 1/\sqrt{2}\,(|up\rangle + |down\rangle)\,,$$
$$|down\rangle \rightarrow 1/\sqrt{2}\,(|up\rangle - |down\rangle)\,. \quad (1)$$

Due to the operation of mirror M_1 we have:

$$|up\rangle \rightarrow |down\rangle\,, \quad (2)$$

and mirror M_2:

$$|down\rangle \rightarrow |up\rangle\,. \quad (3)$$

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[3] Macroscopic bodies also should be described by LWP (the wave function of their center of mass). Even a leading theory of collapse (Ghirardi, Pearle, and Weber 1986) considers reduction of the quantum states of macroscopic bodies only into LWPs.

Knowing the operation of different components, (1) - (3), and using *linearity* of quantum mechanics we can find out the result of the operation of the neutron interferometer:

$$|up\rangle \rightarrow 1/\sqrt{2}\ (|up\rangle + |down\rangle) \rightarrow 1/\sqrt{2}\ (|down\rangle + |up\rangle) \rightarrow$$
$$1/2\ (|up\rangle - |down\rangle) + 1/2\ (|up\rangle + |down\rangle) = |up\rangle\ . \qquad (4)$$

The neutron (LWP), after leaving the beam splitter S_2, moves in the direction "up" and, finally, is absorbed by detector D_1. The explanation is so simple that it is accepted even though it encompasses the existence of highly unintuitive intermediate state of the neutron $1/\sqrt{2}\ (\ |up\rangle + |down\rangle\ )$, the state in which the neutron is simultaneously moving *both* up and down.

We can also understand why the results of the neutron interference experiment cannot be explained if the neutron remembers the path it has passed. When it has a memory variable designated by M_i corresponding to the mirror it has hit, the two waves moving toward detector D_2 are different and, therefore, do not interfere. Indeed, the corresponding terms in the decomposition of the state of the neutron are $-1/2\ |down, M_1\rangle$ and $+1/2\ |down, M_2\rangle$, and they are not cancelled as the terms $-1/2\ |down\rangle$ and $+1/2\ |down\rangle$ are in the expression (4).

6. Preferred basis of the neutron worlds. The neutron inside the interferometer is described by the wave function that is a superposition of two LWPs which are distinguished by the direction of motion and their locations:

$$|\Psi\rangle_{neutron} = 1/\sqrt{2}\ (|up\rangle + |down\rangle)\ . \qquad (5)$$

In the standard approach an attempt to consider a sentient neutron invariably leads to the neutron's schizophrenia. My proposal is to say that during the period of time the neutron is inside the interferometer *there are two neutron worlds*: one corresponding to LWP $|up\rangle$ and the other to LWP $|down\rangle$. In one world there is a neutron moving in the upper half of the interferometer, and in the other there is a neutron only in the lower part.[4] Thus, there are two different neutrons, each having its own trajectory. The crucial physical property, that allows me to consider a part of the total wave function of the neutron as a "whole" neutron in a given world, is that the trajectory of the center of the LWP which is a part of the wave function is absolutely the same as if it were the whole wave function. Physical characteristics of these "partial" neutrons such as mass, spin, etc. are exactly the same as the mass, spin etc. of the whole neutron. The neutron in the upper part cannot know from its immediate experience that in some sense it is only "half" of the neutron.

In equation (5) I decomposed the quantum state of the neutron into the sum of two orthogonal states corresponding to two different worlds. According to the formalism of the quantum theory there are infinite number of ways to make the decomposition of the state into a sum of two orthogonal states. Why did I chose this particular one? Why not, for example, take an alternative way of decomposition of the same state:

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[4] At the moment the neutrons (the neutron ?) reach the mirrors, the neutron in the upper half goes to the state $|down\rangle$ and the one in the lower part goes to the state $|up\rangle$, see equations (2), (3). The state of the neutron from the perspective of the experimentalist remains to be in the form (5).

$$|\Psi\rangle_{neutron} = 1/\sqrt{8}\ ((1+i)\ |up\rangle + (1-i)\ |down\rangle) + 1/\sqrt{8}\ ((1-i)\ |up\rangle + (1+i)\ |down\rangle)\ ? \qquad (6)$$

Because the two components of the decomposition (6) do not correspond to "neutron worlds". Indeed, I made an assumption that neutrons are sentient being as we are. I.e., sentient neutron is not schizophrenic as it has to be in the worlds corresponding to the terms $1/\sqrt{8}\ ((1+i)\ |up\rangle + (1-i)\ |down\rangle)$ and $1/\sqrt{8}\ ((1-i)\ |up\rangle + (1+i)\ |down\rangle)$.

The decomposition (5) is, essentially, the only decomposition into "worlds" in which the neutron is a localized wave packet during the whole period of time and, therefore, has a single experience every moment. It is possible to decompose each term in the superposition (5) into smaller LWPs. If the neutron can distinguish between trajectories of these LWPs, the decomposition should be made into more than two neutron worlds. I consider, here, the situation in which the size of neutron's LWP is smaller than the precision of neutron's spatial senses.

7. Probability as a measure of existence. Let me now discuss the experience of the neutron when it passes through a beam splitter. This is the process when one neutron world transforms into two worlds. The neutron experiences one of the two possibilities: either it scattered and changes its state from $|up\rangle$ to $|down\rangle$ or it remains undisturbed (i.e. $|up\rangle$). Assuming that the neutron does not know MWI, it has no reason to believe that other possibility is also actualized. The neutron which passes through beam splitters many times introduces the concept of *probability*. The situation for the sentient neutron is the same as for the experimentalist who observes the result of the experiment shown on Figure 1. The neutron find itself in detector D_1 or detector D_2, and the observer finds accordingly that detector D_1 or D_2 is triggered. Thus, we can associate the concept of the probability of the observer-experimentalist with the neutron's concept of probability. The beam splitter which we described above by the operation according to equation (1) leads to the probability 1/2 of being found in D_1 and probability 1/2 of being found in D_2. Thus, the neutron passing through this beam splitter ends up with equal probability in one of the states $|up\rangle$ or $|down\rangle$. The experimentalists and the neutron which knows MWI understand that the belief of the neutron (it might be more correct to say "the belief of both neutrons") that there is just one world is an illusion. There are two worlds in parallel: one with the neutron in the state $|up\rangle$ and one with the neutron in the state $|down\rangle$.

Let me introduce the concept of a *measure of existence of a world*. I will give two definitions: one according to experience of a sentient being, and the other from the mathematical formalism. The measure of existence of a world equals to the probability of experiencing this world.[5] The measure of existence of a world equals to the square of the magnitude of the coefficient which multiplies the state corresponding to this world in the decomposition of the whole state into the sum of orthogonal states (worlds). These two definitions are consistent with each other. One might consider the identification of the mathematical measure of existence with probability as an additional axiom in MWI. Note, however, that this is *not* an axiom in mathematical formalism of the theory. This is an interpretational statement: it connects the mathematical formalism with our experience.

In the case of the beam splitter we discussed above, the measure of existence of each neutron world is 1/2. Some other beam splitters do not give equal probability for the two possible results. The general form of the operation of a beam splitter is given by:

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[5] Of course, the probability is defined for the time before the splitting into different worlds occurred.

$$|up\rangle \rightarrow \alpha\ |up\rangle + \beta\ |down\rangle\ . \tag{7}$$

The measure of existence of the world with the neutron in the state $|up\rangle$ is $|\alpha|^2$, and it is $|\beta|^2$ for the world with the state $|down\rangle$. One neutron approaching the beam splitter becomes two different neutrons in two different worlds which are equally real but might differ by their measure of existence.

8. The collapse postulate and why we do not need it. What I have done so far can be called many (two) neutron worlds *interpretation* of a neutron interference experiment. I introduced unusual language, but from the point of view of equations and the results of experiments, I am in a complete agreement with standard approach. However, the MWI of quantum mechanics, in spite of the name, is a *different theory*. The standard approach to quantum mechanics includes all axioms of MWI and it has one more: the postulate of the *collapse* of the quantum state in the measurement process. The collapse postulate has physical consequences which in principle can be tested, although today's technology is very far from performing a decisive experiment.

The collapse occurs when the measurement is performed. There is no collapse of the neutron inside the interferometer and this is why my discussion agrees with standard approach. In order to see the difference let me consider the neutron passing through a beam splitter whose action is described by equation (7) and then detected by detectors D_1 and D_2 (Figure 1). According to MWI, the description of this process is:

$$\begin{aligned} |up\rangle\ |r\rangle_{D_1}\ |r\rangle_{D_2} &\rightarrow (\alpha\ |up\rangle + \beta\ |down\rangle)\ |r\rangle_{D_1}\ |r\rangle_{D_2} \rightarrow \\ &\rightarrow \alpha\ |in\ D_1\rangle\ |in\rangle_{D_1}\ |r\rangle_{D_2} + \beta\ |in\ D_2\rangle\ |r\rangle_{D_1}\ |in\rangle_{D_2}\ , \end{aligned} \tag{8}$$

where $|r\rangle_{D_1}$ signifies the state of detector D_1 "ready", $|up\rangle$ signifies the state of the neutron moving up, $|in\ D_1\rangle$ signifies the state of the neutron when it absorbed by the detector D_1, $|in\rangle_{D_1}$ signifies the state of detector D_1 "neutron in the detector", etc.. Due to the collapse postulate, the final state (8) immediately transforms (with the appropriate probability) to one of the states with definite result of the experiment:

$$\alpha\ |in\ D_1\rangle\ |in\rangle_{D_1}\ |r\rangle_{D_2} + \beta\ |in\ D_2\rangle\ |r\rangle_{D_1}\ |in\rangle_{D_2} \rightarrow$$

$$\rightarrow \left\{ \begin{array}{lll} |in\ D_1\rangle\ |in\rangle_{D_1}\ |r\rangle_{D_2} & \text{probability } |\alpha|^2 & or \\ |in\ D_2\rangle\ |r\rangle_{D_1}\ |in\rangle_{D_2} & \text{probability } |\beta|^2 & \end{array} \right\} \tag{9}$$

The motivation for this step is obvious. The right hand side of (8) indicates that in the end of the measurement the quantum state includes *both* detectors showing "in", i.e. neutron in the detector (as well as both detectors showing "r", i.e. the neutron is not in the detector). The experimentalists, nevertheless, always report that a *single* detector showing "in".

It seems that the collapse postulate is necessary to explain the experimental results. This is, however, not so. The quantum mechanics without the collapse postulate explains the reports of the experimentalists as well. Indeed, let us add the observer as the quantum system. Quantum mechanics describes the process of his observation (when the state of the neutron and detectors described by equation (8)) as follows:

$$(\alpha \, |in\ D_1\rangle \, |in\rangle_{D_1} \, |r\rangle_{D_2} + \beta \, |in\ D_2\rangle \, |r\rangle_{D_1} \, |in\rangle_{D_2}) \, |r\rangle_O \rightarrow$$
$$\rightarrow \alpha \, |in\ D_1\rangle \, |in\rangle_{D_1} \, |r\rangle_{D_2} \, |see\ D_1\ \text{"in"},\ D_2\ \text{"}r\text{"}\rangle_O +$$
$$+ \beta \, |in\ D_2\rangle \, |r\rangle_{D_1} \, |in\rangle_{D_2}) \, |see\ D_1\ \text{"}r\text{"},\ D_2\ \text{"in"}\rangle_O \qquad (10)$$

The formalism of quantum mechanics without collapse shows that there is no observer who sees the neutron being detected by both detectors. Instead, it shows that there are two different observers: one reports that the neutron is detected by D_1 and is not detected by D_2, and the other that the neutron is detected by D_2 and is not detected by D_1. Why were we never confused by their contradicting reports? Because we, in turn, by listening to their reports are also splitting in the same way. And any other experimentalist who observers the detectors splits. Thus, after the experiment there are two worlds: in one of them all agree that the neutron is in D_1, and in the other all agree that the neutron is in D_2. Both worlds are real. If I got a report that the neutron in is D_1, I should not believe that this world is more real than the other. It might be that there is more of one world than of the other, i.e. their measure of existence $|\alpha|^2$ and $|\beta|^2$ might be different. However, the measure of existence of the world has no effect on the "life" in this world. For example, the mass of the neutron in the "small" world is the same as in the "large" one.

9. Test of **MWI**. A wide spread mistake about MWI is that its predictions are identical to predictions of the standard approach. Let me describe here a design of an experiment which distinguishes between MWI and the standard (collapse) approach. My example is similar to the one discussed by Lockwood (1989, p.223); other interesting proposals of testing MWI described by Albert (1986) and Deutsch (1986). All these experiments, of course, cannot be performed in today's laboratory.

Measurement process, say, of the experiment described on Figure 1 including observation of its result by an observer, can be described (if MWI is a correct theory) by Scrödinger's equation with a certain Hamiltonian. A "superman" can build a device with "time reversal" Hamiltonian which can "undo" the measurement. Due to the "time reversal" Hamiltonian devised by the superman the memory of the observer will be erased, the detectors will return to the "ready" state, and the neutron should return to its original place. Thus, if at that time the source of the neutron replaced by a detecter, the later has to detect the neutron with probability one. The neutron, on its "reverse" motion arrives to the beam splitter from two directions and, as in the neutron interference experiment (Figure 3), it continues in a single direction toward the detector. If, however, the collapse took place at some stage of the measuring procedure, say, when the observer looked on the detectors, then the neutron on its "reverse" motion arrives to the beam splitter only from one direction and, consequently, it comes out of the beam splitter in *two* directions (see equation (1)). In this case the probability of detecting the neutron is equal to 1/2. Thus, MWI will be confirmed if the neutron will always be detected by the detector, and it will be refuted if the neutron will be detected in about half of the trials.

Since it is generally believed that the collapse happens when the neutron is detected by a macroscopic detector, an experiment which does not involve human observer is also a reasonable test of MWI. If the detector is microscopic, then even a contemporary design of the device which undoes the interaction between the neutron and the detectors is feasible, and with the progress in technology, we can get closer and closer to the decisive experiment. A significant step toward this goal has been done recently by opening a new experimental field: two-particle interferometry (Horne, Shimony, and Zeilinger 1989). While in the case of neutron interferometer, the two worlds which were brought into one differed only due to a trajectory of a *single* neutron, now the worlds which interfere with each other differ because of trajectories of *two* particles.

10. MWI as a universal theory. According to MWI the Universe, everything that exists, is characterized by a single quantum state, the State. The time evolution of the State is completely deterministic (it is given by Shrödinger equation).

Essentially, the Universe *is* the State. This might sound strange because according to the standard use of language an object is not a state, it can be *in* a given state. The existence of the object comes before and independently of its state. However, modern science says that all objects are made out of identical (elementary) particles of a few types. What specifies, defines an object is a *configuration*, a state of these particles. The meaning of a sentence:" Here there is a dog", is not that here there are this number of protons, that number of neutrons, etc.. Many other objects may be combined out of the same particles. The important part is that the state of these particles has a certain form, the form of the dog.

The world, as we commonly understand it through our experience, corresponds to a tiny part of the Universe, i.e. to the tiny part of the State. The State $|\Psi\rangle$ can be decomposed into a superposition of orthogonal states $|\psi_i\rangle$ corresponding to different worlds:

$$|\Psi\rangle = \sum_i \alpha_i \, |\psi_i\rangle \qquad (11)$$

and our world corresponds to one of the terms in this superpositions. The coefficients α_i which multiply (normalized) states $|\psi_i\rangle$ yield measures of existence $|\alpha_i|^2$ of different worlds. Sentient beings in these worlds do not experience the absolute magnitude of the measure of existence of their worlds. The measure of existence becomes relevant when it seems to us that one out of several possible things going to happen (like the neutron going to be detected by one of the detectors, Figure 1). The ratio of measures of existence of the worlds corresponding to the different outcomes yields the ratio of *probabilities* for these outcomes. See Lockwood (1989, pp.230-232) for pictorial explanation of this rule.

The measure of existence of our world is not the maximal among the worlds, but it is reasonably large. Although the measure of our world is significantly smaller than the measure of the world in which all quantum experiments give the maximally probable outcomes, the measure of all worlds corresponding to the outcomes deviating from the optimum similarly to our world, is much larger. In fact, the assumption that probability proportional to the measure of existence, yields exactly statistical predictions of quantum theory.

The basis of the decomposition (11) of the Universe is determined by the requirement that individual terms $|\psi_i\rangle$ correspond to sensible worlds. The consciousness of sentient beings who are attempting to describe the Universe *defines* this basis. I want to emphasize that the choice of the basis has no effect whatsoever on the time evolution of the Universe. The concept of *world* in MWI is not part of the mathematical theory, but a subjective entity connected to perception of the observer (e.g. sentient neutron), such that it corresponds for human beings to our usual notion of the world. In this context one can understand the idea of Wigner (1962) about collapse caused by consciousness of the observer. Not that there is any new law which describes the effect of consciousness on physical processes, but the conscious observer defines the basis of decomposition of the Universe into the worlds causing, effectively, in each world a collapse during quantum measurement.

I believe that the decomposition of the Universe into sensible worlds is, essentially, unique. The decomposition, clearly, might differ due to a coarse or fine graining, such as decompositions by the neutron and and by the experimentalist performing the neutron interference experiment (one experimntalist's world is two neutron worlds). But to have an essentially different decompositions would mean having an Escher-type picture of the whole Universe continuously evolving in time.

11. How many worlds?[6] This is a popular question among the opponents of MWI. The estimates of the number of worlds yield astronomical numbers: 10^{100+}, and many reach the conclusion that MWI is absurd. However, one should not worry because of this large number because the number of worlds *is not* a physical parameter in the theory. The physical theory is about the Universe, *one* Universe. Worlds are *subjective* concepts of the observers.

A world is a sensible description. It can be characterized by the values of a set of variables. If the State (of the Universe) is known, one can calculate the value of a projection operator corresponding to these values of the set of variables. It is equal to the measure of existence of this world. If the measure is zero, the world does not exist. I do not know the State. Therefore, I do not know if that or another world exist. I do know that the world in which I wrote this paper exists. I also have knowledge about quantum experiments with possible different outcomes which were performed. Therefore, I know that there are other worlds. And the worlds continue to multiply. By performing quantum experiments with a priori uncertain outcomes I am certain that I increase the number of worlds. Especially effective for multiplying worlds is listening to a detector of a radioactive decay; we get a continuum: for each different instant of the detection there is a different world. Although there are very many worlds from the perspective of human being, probably, not as many as in the modal realism approach (Lewis 1986) in which *every* possible world exists.

12. Locality of the preferred basis. One can make a conjecture about a theory of evolution according to which conscious observers evolved with local senses as we posses. Consciousness is a collection of thoughts. Thought is a causal chain. All interactions are *local*. Theory of relativity is correct, i.e. instantaneous communications are impossible. These are the reasons for causal chains of our thoughts being consist of local events. The neutron, "created" in this work "in the human image", can understand local events such as being kicked by a mirror, while it cannot comprehend being in two places simultaneously. The neutron distinguishes between locally described worlds given by equation (5) and cannot distinguish between orthogonal nonlocal states given by equation (6).

Physics explains why an observer who "thinks" in the concepts of nonlocal superpositions is not evolutionary favorable. Imagine an observer who can distinguish between two nonlocal orthogonal states of a macroscopical system. He "thinks" in the concepts of nonlocal superpositions and acts differently according to orthogonal nonlocal states. For example, if the state of the neutron and the detectors in the experiment described on the Figure 1 is

$$1/\sqrt{2}\ (\ |in\ D_1\rangle\ |in\rangle_{D_1}\ |r\rangle_{D_2} + |in\ D_2\rangle\ |r\rangle_{D_1}\ |in\rangle_{D_2}) \ , \qquad (12a)$$

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[6] Careful critical analysis of different versions of MWI under this title was given by Healey (1984).

he makes a record "+" in his notebook, and if the state is:

$$1/\sqrt{2}\ (\ |in\ D_1\rangle\ |in\rangle_{D_1}\ |r\rangle_{D_2} - |in\ D_2\rangle\ |r\rangle_{D_1}\ |in\rangle_{D_2}) \ , \tag{12b}$$

he makes a record "-". However, these records will not be helpful because due to the local interaction with the environment, a very short time later, the system in both cases will cease to be in a pure quantum state (Zurek 1986). The system, consisting of the neutron and two detectors, will be described by a mixture with equal probability to be found in the states (12*a*) and (12*b*). Compare this with the observer who makes local measurement that distinguishes between the states:

$$|in\ D_1\rangle\ |in\rangle_{D_1}\ |r\rangle_{D_2} \tag{13a}$$

and

$$|in\ D_2\rangle\ |r\rangle_{D_1}\ |in\rangle_{D_2}) \ . \tag{13b}$$

The records of the latter will be accurate even after the interaction with the environment.

My discussion shows that the MWI does not need an additional axiom about preferred basis. Thus, I do not consider the appeal for such (see Squires 1990 and references there) as necessary. However, I do consider these works important as the study of how a given observer defines its worlds. In this context also very important an extensive research of the role of the environment in the measuring process (see, for example, Zureck 1986). It shows stability of local events in the causal chain of a human observer. Another significant contribution to the understanding of the preferred basis of the observer in MWI is given by Putnam (1981). Reading his work, however, one has to remember that MWI is a *universal* picture and as such does not discriminate between the world in which I wrote this paper and other worlds.

13. God does not play dice. This is probably the most famous objection of Einstein to quantum theory. The quantum theory with collapse introduced a new type of probability, not an effective probability due to our ignorance about exact details of the state prior to a measurement, but an objective probability. Quantum events are such that even God cannot predict them. Bell (1964) proved that unless God has some nonlocal features, which is against even more holy principles of Einstein, God, in fact, cannot predict the outcomes of some quantum measurements performed on a simple system of two spin-$\frac{1}{2}$ particles. Philosophers are frequently unhappy with a deterministic Universe, but they even more unhappy with the genuinely random Universe. The MWI solves this difficulty: God does not play dice. Everything is deterministic from the point of view of God. Everything evolves in time according to Shrödinger's equation. At the same time, there is an explanation why it seems to us that there is a genuine random process when we make a quantum measurement.

The most difficult problem in MWI is the *interpretation of probability*. The difficulty to explain probability in the framework of MWI arises because it is a completely novel concept that, not surprisingly, corresponds to a novel, genuinely random, process. Before, we always used the concept of probability when one out of several possibilities could take place; while according to MWI *all* these possibilities are realized in the Universe.

How the *deterministic* evolution of the Universe can explain the concept of probability? This difficulty led to several misconceptions about MWI. Many understood that splitting of the worlds is something that *actually* happens, and not just a subjective property of a sentient observer as I described it. Another popular statement is that *all* worlds must have *equal* probability. An interesting consistent theory which incorporate these assumptions is many-minds interpretation by Albert and Lower (1988). *I*, however, do not find enough justification for introducing nonphysical and supervenient concept of "minds". It does not seem preferable *t* introducing the concept of "measure of existence of a world".

It seems to me that the concept of probability is paradoxical in MWI only when one does not free himself from a "single world" type of thought according to which even the existence of several parallel worlds is a paradox. When one accept the MWI picture of the Universe, understanding that the world as we perceive it corresponds, in the mathematical formulation of the theory, to a particular term in the formula for the whole Universe, it is very natural to accept that a probability of a given outcome proportional to the absolute value of the corresponding term (measure of existence of the corresponding world).

Until today continues an extensive debate (see Ballentine (1971), Kent (1989) and references there) about the possibility, using MWI, of *deriving* the quantum probability rule from a weaker probability postulate. The claim is that from the postulate which says that the the probability of the result i is zero when $|\alpha_i|^2 = 0$ and is one when $|\alpha_i|^2 = 1$ (see decomposition (11)) *follows* that the probability for the result i equals to $|\alpha_i|^2$ for *any* value of α_i. I agree here with the opponents of MWI that the assumption of the existence of many worlds does not help to derive quantum law of probability. It seems to me that this debate sociologically played a negative role for MWI. Failure of MWI of deriving quantum law of probability frequently considered as a proof of its inadequacy, in spite of the fact that any other interpretation is not better in this respect.

14. Why MWI? My belief in MWI does not based on Lewis' philosophical arguments (1986) in favor of the thesis of plurality of worlds. For me, the crucial argument in favor of MWI is that it does not need to explain the collapse of the wave function. It seems to me that the bad features of the collapse cannot be overestimated. "The reduction [collapse] postulate is an ugly scar on what would be a beautiful theory if it could be removed", the phrase of Gottfried (1989), represents feelings of many physicists. There is no clue when exactly the collapse occurs. If it does occur, it seems impossible to avoid contradictions with special relativity (Aharonov and Albert 1980). In spite of enormous efforts in the last half century, there is no satisfactory physical explanation of the collapse. Extremely divergent proposals for the cause of the collapse, like consciousness, gravitation, new genuine random processes, etc. indicate the difficulties in the project of explaining the collapse.

For me, an important positive feature of MWI is the elimination of conceptually unpredictable outcomes from the fundamental theory of the Universe (God does *not* play dice). I wish to believe, that at least in principle, Science can explain everything.

Most physicists who favor MWI do it because it allows to consider the quantum state of the Universe, the basic concept in quantum cosmology. The standard approach requires an *external observer* for a system whose quantum state is considered and, therefore, is unable to deal with the quantum state of the whole Universe.

Although, as far as I know, nobody has done it explicitly, MWI can be extended to the relativistic domain. This belief based on the fact that all paradoxes of superluminal changes disappear with the removal of the collapse.

MWI yields a novel basis for investigation of the relation between mind and matter (Lockwood 1989). According to MWI we are quantum states, even parts of the superposition that is the whole State. Dennett's analysis shows that it is not so paradoxical idea that the mathematically described objects might have experiences even of a "free will" (Dennett 1984).

If MWI is true then it is meaningful to make an attempt to explore the "other" worlds. We can investigate historical records about quantum measurement-type interactions. With the knowledge that all worlds corresponding to the possible outcomes of all quantum measurements exist, and with the appropriate measure of existence, we can get some information about the other worlds of the Universe. This information might be relevant for the theory of evolution. For example, for resolving a paradox about the Universe not having enough time and not enough particles to reach (according to contemporary biological evolution theory) today's state.

Although one does not have to believe in MWI in order to design a machine which employs quantum interference on macroscopic scale, it is clearly more natural to discuss these possibilities when one should not worry about "miraculous" collapses, but only about quantum correlations appearing due to Shrödinger's equation. It is not a coincidence that the pioneer of a "quantum parallel processing" is an enthusiastic proponent of MWI - Deutsch (1985). While it is hopeless to reach the "other" worlds which are already splitted from "our" world, it is much more feasible to create carefully several worlds and reunite them later.

The last is a practical reason. (Please, forgive me, my friends.) If the physics community will accept MWI (or any other noncollapse theory) as a leading interpretation, a significant time which is spend by theoretical physicists on constructing various collapse theories can be saved. My feeling is that these efforts should be resumed when and if an experimental evidence for a failure of Shrödinger's equation will be obtained, the search for which has to be continued.

15. Causal interpretation. As a physical theory the MWI is more economical than any other quantum theory without collapse. If we assume that there is no collapse, then we at the same time assume the existence of the State of the Universe with all its "branches" corresponding to all innumerable worlds of MWI. So all the complexity of MWI is there and, in addition, there is something else. Let me, however, to touch here one other leading noncollapse interpretation.

A very interesting noncollapse theory is a "causal interpretation". The most credit for it should be given to Bohm (1952), however earlier de Broglie (1927) and later Bell (1981) also contributed to this beautiful picture. In addition to the quantum state of the Universe there is a *point* in configuration space of locations of all particles. The motion of this point is governed by values of the wave function in the immediate vicinity of the point according to a simple equation (especially simple in Bell's version of the theory). Only this point corresponds to "reality", while the wave function (the quantum state) is a secondary entity, whose purpose is to be *a* "pilot" of the point. Thus, there is only one "real" world. Paradoxes of nonrelativistic quantum theory are explained beautifully by the causal interpretation. The particles, after all, do have trajectories. The neutron (the corresponding coordinate of the "point") in the neutron interference experiment passes through one of the possible trajectories, while the corresponding wave passes through both of them. The theory is also deterministic from the point of view of God, so he does not play dice.

So, it seems that the causal interpretation has all good properties of MWI and it has only a single world: surely, a desirable feature. I, however, do not consider it preferable to MWI (see also discussion by Zeh, 1988). First, I do not see that the causal interpretation really gets rid of the other worlds. If a quantum state, which is a wave function in a shape of a man, continues to move (to live?!) exactly as a man does, in what sense it is not a man? My second objection is more technical. Causal interpretation is not covariant (the description of the "point" in the configuration space is not relativistically invariant), and it seems that there is no nice way to generalize it to relativistic domain.

16. "I" in MWI. The worlds are continuously splitting, and in many of them there is I. The splitting of "I" finds many innocently sounding questions to be ill defined. When will I die? When will Lev Vaidman, born in Leningrad at 1955, die? Although I am Lev Vaidman and I was born at 1955, the above two questions are different and both of them are ill defined. Lev who was born in 1955 had many splittings even before 1990. All these many Levs, including the one which wrote these paper in 1990, will continue to split in the future. And different Levs will die at different times.

In our standard approach, which has the whole history of human beings as its basis, every time when there is a situation corresponding to a splitting of "I", only one "I" continues to exist. This particular "I" is the one which I care about. This is the "I" for whom I wish a long happy life. But if I *know* that all "I"s exist, and that there is no one particular, real "I" among them – what then? Should I care about all "I"s, or should I care more about some of them and less about the others?

In fact, even in the case that I do not believe in the existence of all "I"s, I do care about all of them. Consider the situation in which I was told that I will spend the next week on one of several isolated islands, and the choice of the island will be according to the outcome of a quantum measurement. I know the probabilities for possible outcomes of the measurement and I can distribute a certain amount of food between these islands. Even if I think that I will spend the next week on only one of the islands, I will put some food on more than one island. I will put more food on the islands corresponding to the outcomes which have higher probabilities as they are given by quantum theory, and I will care less about the islands corresponding to smaller probabilities. If the probability for a certain outcome is zero, I will not care about the corresponding island at all. I care about different islands according to the probability of ending up there, i.e. according to the square of the absolute value of the scalar product between the initial quantum state the and corresponding eigenstate of the quantum variable.

According to MWI, I will spend the next week on all islands which correspond to the outcomes with non zero probability. The difference between different islands will be the *measure of existence* of the corresponding worlds. This measure of existence is proportional to the square of the absolute value of the scalar product of the quantum state corresponding to me being there and the State (of the Universe). The measures of existence of worlds in which I am on different islands are proportional to the probabilities of me being there according to the standard approach. Therefore if I, believing in MWI, accept the principle of caring about different "I"s according to the measure of existence of worlds in which these "I"s live, then I will behave as everybody does. A natural principle of *caring about different worlds according to their measure of existence* leads to a "normal" behavior of a believer in MWI.

There is, however, a way of reasoning which might lead to a strange behavior. Let me assume that one evening I have a choice of going out with M. or with N., and I cannot make a decision. I can spin a coin and then I will go out *either* with M. *or* with N. according to the results of this classical experiment: heads or tails. But, since I believe in MWI, it seems that I can do better. If, instead of the classical coin, I use quantum measurement with two possible outcomes, then I will go out with two girls simultaneously. More precisely, I will split into two "I"s: one will go out with M. and another with N.. So no real bigamy is possible, but still, both of the "I"s of the future are very closely connected to the "I" now. The principle of caring about one's descendants together with the desire to accomplish as much as possible might cause me to think that the use of a "quantum coin" is preferable. It is not so clearly a preferable situation since the measure of existence of each "I" in the case of using the quantum choice will be just half of the measure of existence of the one future "I" when I use the classical coin, but it is clearly a *different* situation. The classical morals cannot give me any clue to decide which of these two possibilities is better for me. In any way, using a coin in this situation is a questionable behavior, but in the case of using a quantum coin, I certainly will be advised to see a psychiatrist.

One can continue to philosophize as I did in this section. One can also formalize the picture of the Universe which I have drawn above. And I believe that we, indeed, should proceed in these directions. However, this further research will be meaningful after reaching some consensus about validity of arguments presented in the previous sections of this work.

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