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On schizophrenic experiences of the neutron or why we should believe in the many-worlds interpretation of quantum theory

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Abstract *This is a philosophical paper in favor of the many-worlds interpretation (MWI) of quantum theory. The necessity of introducing many worlds is explained by analyzing a neutron interference experiment. The concept of the "measure of existence of a world" is introduced and some difficulties with the issue of probability in the framework of the MWI are resolved.*

> 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.
>
> Bertrand Russell

1. Introduction

There are many interpretations of quantum mechanics, and new ones continue to appear. I believe that the many-worlds interpretation (MWI) introduced by Everett (1957) is the best candidate for *the* interpretation of quantum theory. My belief is not based on a philosophical affinity for the idea of plurality of worlds as in Lewis (1986), but on a judgment that the physical difficulties which arise if we assume that there are no worlds beyond the one we see are too serious.

The MWI is not a theory about many *objective* "worlds". A mathematical formalism by itself does not define the concept of a "world". The "world" is a subjective concept of a sentient observer. All (subjective) worlds are incorporated in *one* objective Universe. I think, however, that the name many-worlds interpretation does represent this theory

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fairly well. Indeed, according to the MWI (and contrary to the standard approach) there are *many worlds* of the sort we call in everyday life "the world". And although the MWI is not just an *interpretation* of quantum theory—it differs from the standard quantum theory in certain experimental predictions—interpretation is an essential part of the MWI; it explains the tremendous gap between what we experience as our world and what appears in the formalism of the quantum state of the Universe. Schrödinger's equation (the basic equation of quantum theory) predicts very accurately the results of experiments performed on microscopic systems and it also implies the existence of many worlds. The purpose of the collapse postulate, which distinguishes the standard approach from the MWI, is to escape the implications of Schrödinger's equation for the existence of many worlds.

Today's technology does not allow us to test the existence of the "other" worlds. So only God or "superman" (i.e. a superintelligence equipped with supertechnology) can take full advantage of the 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 the purposes of exposition, I shall attribute to the neutron the ability to feel, to remember, and to understand, but of course, the validity of the MWI held by a human observer 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 a neutron interferometer and show that a sentient neutron passing through the interferometer *must* have schizophrenic experiences. In Section 4, I introduce the neutron's MWI and explain how it solves the problem of neutron's schizophrenia. In Sections 5–7, I continue the discussion of the MWI using the example of a neutron interferometer. Sections 8 and 9 are devoted to the central issue of this paper, the concept of probability in the MWI. In Section 10 I present, and in Sections 11–14 I discuss, the MWI of the Universe. In Section 16, I summarize the arguments in favor of the MWI.

2. The neutron beam splitter

Let me start with an analysis of a simple experiment. A neutron passes through a beam splitter S toward detectors D_1 and D_2 (see Figure 1). The outcome of this experiment, as reported by numerous experimenters, is 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 experimenter sees only one triggered detector. There are two distinct possibilities and only one of them is realized.

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 experimenter, the record in his notebook, etc. In the standard approach, only *one* of these worlds exists. According to the MWI, however, both possibilities of the experiment are actualized. Both detectors D_1 and D_2 are triggered, both outcomes are seen by the experimenter, both results are written down in the notebook, etc. When an experimenter reports to me that the neutron was detected by D_1, I, Lev Vaidman (a believer in the MWI), *know* that there is also a world in which Lev Vaidman 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.

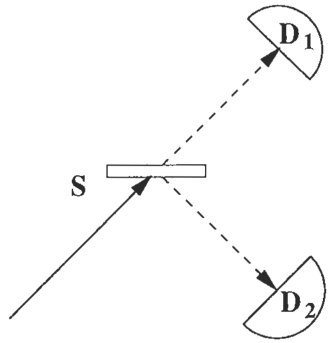

Figure 1. *The neutron beam splitter.*

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 is either scattered through a given angle or continues in a straight line without being disturbed. The neutron has a single trajectory. We can bolster our confidence that the single trajectory is the correct description by considering the results of the experiments with a mirror and two beam splitters in either one of the configurations of Figure 2. The prediction for the outcomes of these experiments is that in half of the trials the neutron is not detected by either of the two detectors (when it takes the trajectory without the mirror), and in the other half it is 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 systems 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.

3. The neutron interferometer

The neutron interferometer is an experimental device that can be found in several laboratories in the world; for a comprehensive review see Greenberger (1983). Making the assumption of the previous section it is impossible to explain the results of the neutron interference experiment. As we shall see, these results, combined with the assumption that there is only one world for the neutron, compel the neutron to have schizophrenic experiences.

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 through a given angle or continues in a straight line without being disturbed, we conclude that each neutron takes one of the four trajectories $S_1M_1S_2D_1$, $S_1M_1S_2D_2$, $S_1M_2S_2D_1$, $S_1M_2S_2D_2$. Therefore, the neutrons have to be detected at random by detectors D_1 and D_2. But the experiment (appropriately tuned) does not show what is expected! *All* the neutrons are detected by detector D_1.

We cannot explain the experimental results by the picture of a single trajectory for

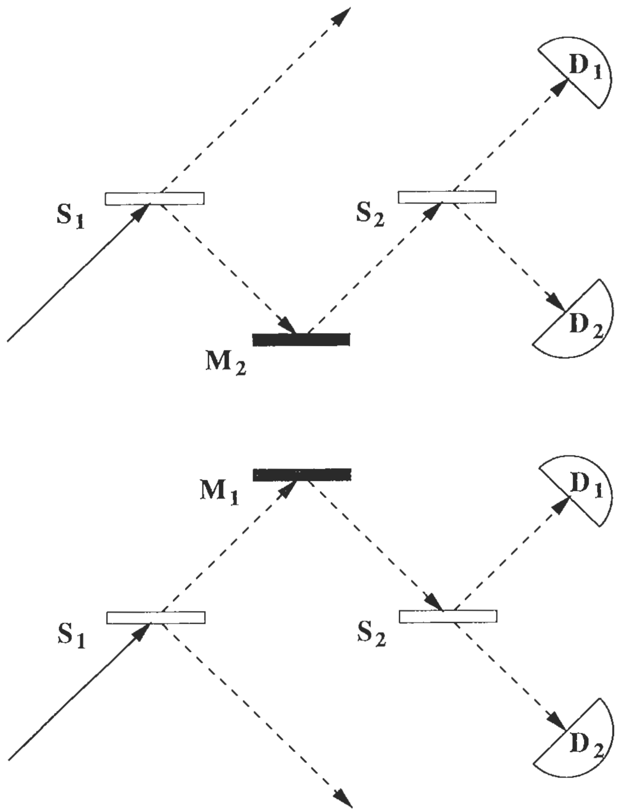

Figure 2. *Two arrangements of neutron beam splitters and a neutron mirror.*

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, therefore, have schizophrenic experiences.[2]

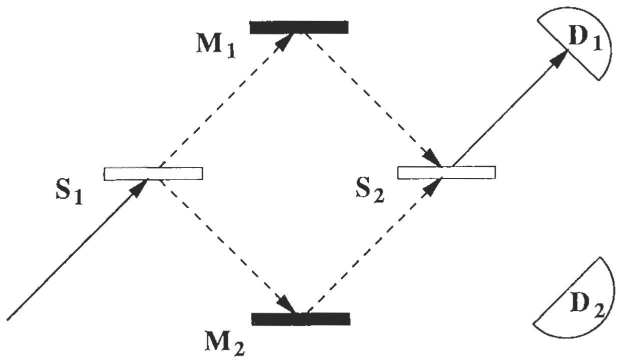

Figure 3. *The neutron interferometer. When the interferometer is properly tuned, the two waves coming toward* D_2, *one from* M_1 *and one from* M_2 *interfere destructively and* D_2 *never clicks.*

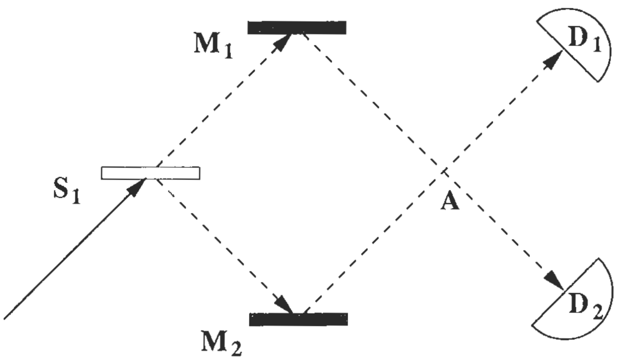

Figure 4. *Neutron interferometer without second beam splitter. Each of* D_1 *and* D_2 *fire* 50% *of the time. No scattering in the area* A *is observed.*

4. Two neutron worlds

To avoid positing schizophrenic neutrons, I propose that during the time the neutron is inside the interferometer the world of the experimenter encompasses *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, was kicked by mirror M_1 and bounced 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, questions which are illegitimate according to the standard approach.

The neutron in one neutron world does not know (unless it has studied quantum mechanics and believes in the MWI) about the existence of its "twin" in the other world. In the same way, most of us do not think that in addition to the world we experience there are other worlds present in the space-time. The experimenter, 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 the two neutrons meet each other at point A, the original location of beam splitter S_2. 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 from each other. But in this experiment (shown in Figure 4), there is no scattering whatsoever: the rate of detection of neutrons by D_1 (D_2) is *not* affected in any way when we eliminate the twin-neutrons by placing an absorption screen before mirror M_1 (M_2).

Let us discuss again the neutron interference experiment (Figure 3). The hypothesis of many (two in this case) worlds solves the problem of the neutron's schizophrenia inside the interferometer, but it seems that we are 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? Did it hit M_1 or M_2? As we will see in the next section, quantum theory tells us that the neutron *cannot* retain memories about which trajectory it took (in which world it "lived"). That is, quantum mechanics does explain why the neutron is detected by D_1, but only if the neutron has no internal variable that "remembers" (after the neutron leaves the interferometer) which trajectory the neutron has taken. Neutron memory is not ruled out completely: the neutron might remember its trajectory while it is still inside the interferometer, but the 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", while inside the interferometer, which path it takes. One of the devices that can serve as a beam splitter for a neutron is a specially designed magnet (a Stern–Gerlach apparatus). In this case, the path of the neutron is correlated with the value of an internal variable called spin, so the neutron has the spin to remind itself of its path while it is inside the interferometer. However, the second magnet, replacing the second beam splitter, erases the correlation and the memory once the neutron leaves the interferometer (it must erase the correlation in order for interference effects to occur).

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? Yes, the same reason that we have: this hypothesis explains why, after passing through the interferometer, the neutron always ends up in detector D_1. We will see next, how quantum theory (with many worlds) explains this experimental fact.

5. Quantum mechanical explanation

In standard quantum mechanics particles do not and *cannot* have trajectories. 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 at a given point yields the probability per unit volume of finding the particle there. Frequently, the spatial wave function spreads out significantly and then there is no answer to the question: where is the particle? Nevertheless, physicists do consider trajectories of particles. What physicists mean when they say that the neutron takes a given trajectory is that the spatial wave function of the neutron is a localized wave packet (LWP) whose center moves on this trajectory. Inside the interferometer the wave function of the neutron is not a LWP and, consequently, the neutron has no trajectory. However, when the neutron leaves the beam splitter S_2, its wave function again becomes a LWP, the LWP which moves toward detector D_1. This is the quantum-mechanical explanation why the neutron is never detected by detector D_2. Let me now demonstrate this quantum interference effect using some formulas.

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

$$
\begin{aligned}
|up\rangle &\rightarrow 1/\sqrt{2}(|up\rangle) + |down\rangle),\\
|down\rangle &\rightarrow 1/\sqrt{2}(|up\rangle - |down\rangle).
\end{aligned} \tag{1}
$$

The action of mirror M_1 is

$$|up\rangle \rightarrow |down\rangle, \tag{2}$$

and of mirror M_2,

$$|down\rangle \rightarrow |up\rangle. \tag{3}$$

Knowing the action of components (1)–(3), and using the linearity of quantum mechanics, we can find out the state of the neutron leaving the interferometer:

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

The neutron LWP, after leaving the beam splitter S_2, moves in the direction "up" and is absorbed by detector D_1. This explanation is so simple that it is generally accepted even though it involves an intermediate state of the neutron moving *both* up and down at the same time.

We can also understand why the neutron interference experiment cannot be explained if the neutron remembers which path it took. If it has a memory variable M_i corresponding to which mirror it hit, the two waves reaching detector D_2 are different and, therefore, do not interfere. The corresponding terms in the state of the neutron, $-1/2|down, M_1\rangle$ and $+1/2|down, M_2\rangle$ are not canceled as are the terms $-1/2|down\rangle$ and $+1/2|down\rangle$ in equation (4).

The neutron inside the interferometer is described by the wave function that is a superposition of two LWPs distinguished by their direction of motion and location:

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

In the standard approach, a sentient neutron would invariably be schizophrenic. My proposal is that during the period of time the neutron wave function is inside the interferometer *there are two neutron worlds*: one corresponding to LWP $|up\rangle$ and the other to LWP $|down\rangle$. In each world there is a neutron with its own trajectory. We can view a part of the neutron wave function as a "whole" neutron (in a given world) because physical characteristics of the "partial" neutron, such as mass, spin, etc., are exactly the same as the characteristics of the whole neutron. The trajectory of each LWP (inside the interferometer where there are no splittings) is just what it would be if it were the whole wave function. So, the neutron in each world cannot know from immediate experience that in some sense it is only "half" a neutron. Indeed, any physical measurements performed by the "half" neutron moving in one arm of the interferometer would yield exactly the same results as the same measurements performed by the "whole" neutron moving in this arm.

6. The preferred basis of the neutron worlds

In the previous section I decomposed the quantum state of the neutron (5) into a sum of two orthogonal states corresponding to two different neutron worlds. In the formalism of quantum mechanics there are infinitely many ways to decompose the state into a sum of two orthogonal states. Why did I choose this particular one? Why not, for example, take an alternative decomposition of the same state:

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

The reason is that the two components in equation (6) do not correspond to "neutron worlds". Consider, for example, the component $1/\sqrt{8}((1+i)|up\rangle + (1-i)|down\rangle)$. It is a superposition of two LWPs separated by macroscopic distance. Therefore, in the world corresponding to this component the neutron must have schizophrenic experiences of being in two places simultaneously. I have made an assumption that neutrons are similar to us, i.e. a sentient neutron is not schizophrenic, and this assumption rules out the decomposition to the worlds (6). The decomposition (5) is, essentially, the only decomposition into "worlds" in which the neutron is a LWP during the whole period of time and, therefore, has a single experience at every moment. But I agree that it is possible to decompose each term in equation (5) into smaller LWPs; and *if* the neutron can distinguish between the trajectories of these LWPs, the decomposition should be made into more than two neutron worlds.

7. The collapse postulate and why we do not need it

What I have done so far may be called the many (two) neutron-worlds *interpretation* of a neutron interference experiment. I have introduced unusual language, but with regard to equations and results of experiments, I am in complete agreement with the standard approach. However, the MWI of quantum mechanics, in spite of its name, is a *different theory*. The standard approach to quantum mechanics includes all axioms of the MWI and it has one more: the postulate of the *collapse* of a 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 permitting a decisive experiment.

Collapse occurs when a measurement is performed. There is no collapse of the neutron state inside the interferometer, and so my discussion agrees with the standard approach. In order to display the differences between the MWI and the standard approach let us consider a neutron passing through a beam splitter and detected by detectors D_1 and D_2 (Figure 1). The neutron passing through the beam splitter described above in equation (1) assigns equal probabilities to the states $|up\rangle$ and $|down\rangle$. 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

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

Then, according to the MWI, the description of the whole process is:

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

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

$$\begin{aligned} &\alpha|in\ D_1\rangle|in\rangle_{D_1}|r\rangle_{D_2} + \beta|in\ D_2\rangle|r\rangle_{D_1}|in\rangle_{D_2} \rightarrow \\ &\rightarrow \begin{cases} |in\ D_1\rangle|in\rangle_{D_1}|r\rangle_{D_2} & \text{(probability } |\alpha|^2\text{) or} \\ |in\ D_2\rangle|r\rangle_{D_1}|in\rangle_{D_2} & \text{(probability } |\beta|^2\text{).} \end{cases} \end{aligned} \tag{9}$$

The motivation for this step is obvious. The right-hand side of (8) indicates that at the end of the measurement detector D_1 registers "*in*" *and* detector D_2 registers "*in*" (as well as that both detectors show "*r*"). The experimenters, however, always report that a *single* detector registers "*in*".

It seems that the collapse postulate is necessary to explain the experimental results. This, however, is not the case. Quantum mechanics without the collapse postulate explains the reports of the experimenters as well. Indeed, let me also consider the experimenter as a quantum system. Quantum mechanics describes the process of observation (when the state of the neutron and the detectors are described by equation (8)) as follows:

$$\begin{aligned}(\alpha|in\ D_1\rangle|in_{D_1}|r\rangle_{D_2} + \beta|in\ D_2\rangle|r\rangle_{D_1}|in\rangle_{D_2})|r\rangle_E \to \\ \to \alpha|in\ D_1\rangle|in\rangle_{D_1}|r\rangle_{D_2}|see\ D_1\text{“}in\text{”},\ D_2\text{“}r\text{”}\rangle_E \\ + \beta|in\ D_2\rangle|r\rangle_{D_1}|in\rangle_{D_2})|see\ D_1\text{“}r\text{”},\ D_2\text{“}in\text{”}\rangle_E \qquad (10)\end{aligned}$$

where $|see\ D_1\text{“}in\text{”},\ D_2\text{“}r\text{”}\rangle_E$ signifies the state of the experimenter seeing D_1 clicks, D_2 "ready", etc. In quantum mechanics without collapse, there is no experimenter who sees the neutron being detected by both detectors. Instead, there are two different experimenters: one reports that the neutron is detected by D_1 and is not detected by D_2, and the other reports that the neutron is detected by D_2 and is not detected by D_1. Why are we never confused by their contradictory reports? Because we, in turn, by listening to their reports, are also splitting in the same way. And any other experimenter who observes the detectors splits. 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 is in D_1, I should not believe that this world is more real than the world in which the neutron is in D_2.

In Section 9 I will introduce the concept of "measure of existence of a world" and the measure of existence of the world with the neutron in D_1 is, in general different from that with the neutron in D_2, i.e. in some sense, there is "more" of one world than of the other. However, I still should not say that one world is more real than the other. There is no reason whatsoever to believe that the measure of existence of the world in which you now read this paper is maximal among all worlds, but nevertheless it is as real as it can be.

8. The concept of probability of a believer in the MWI

Let me come back to the gedanken experiment with a sentient neutron. I shall discuss the experience of the neutron as it passes through a beam splitter. This is the process in which one neutron world transforms into two worlds. The neutron experiences one of two possibilities: either it scatters or it remains undisturbed. Assuming that the neutron does not know the MWI, it has no reason to believe that the other possibility is also realized. The neutron which passes through many beam splitters develops a concept of *probability*. The situation for the sentient neutron is the same as for an experimenter observing the result of the experiment of Figure 1. The neutron finds itself in detector D_1 or detector D_2, and the experimenter finds accordingly that detector D_1 or D_2 clicks. Thus, we can identify the experimenter's concept of probability with the neutron's concept of probability. The neutron passing through the beam splitter described above in equation (7), has the probability $|\alpha|^2$ to be found in D_1 and the probability $|\beta|^2$ to be found in D_2, see equation (9).

It is more difficult to define a concept of probability for those experimenters and those neutrons who know the MWI. They 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 the other with the neutron in the state $|down\rangle$. Thus, the phrase "the probability for the neutron to be found at D_1" seems senseless. Indeed, it is not clear what "the neutron" in this phrase means, and it seems that whatever neutron we consider, we cannot obtain $|\alpha|^2$ for the probability. For the neutron passing through a beam splitter the probability to end up at D_1 *as opposed to* D_2 is meaningless because this neutron becomes *two* neutrons. The two new neutrons are identified with the old one: the neutron detected by D_1 and the neutron detected by D_2 *both* entered the beam splitter. The new neutrons have no identity problem; the neutron at D_1 has the direct experience of being at D_1 as opposed to D_2, but it seems that the probability for that neutron to be at D_1 is 1; similarly, the neutron at D_2 has probability 0 to be at D_1, none of them have probability $|\alpha|^2$.

I propose that the answer to this conundrum lies in the fact that while *we* cannot assign any other number to this probability, the neutron *can*. I will introduce this proposal with intuitive gedanken experiment, and then make a formal proposal. In order to see how the neutron can assign the quantum probabilities in this case, suppose that the neutron (not enjoying beam splitters) took a sleeping pill and slept until it reached a detector. Now, if it awakes inside the detector but has not yet opened its eyes, the neutron (an expert in quantum mechanics) can say: "I have a probability $|\alpha|^2$ to find myself in D_1". This is an "ignorance-type" probability. We, like any external system, cannot be ignorant about the location of the neutron since we identify it on the basis of its location, while each sentient neutron does not need information to identify itself.[3] The second new neutron, the one at D_2, before opening his eyes has exactly the same belief: "I have a probability $|\alpha|^2$ to find myself in D_1". The neutron entering the beam splitter turns into two neutrons which have the same belief about probability. This allows us to associate the probability for the neutron entering the beam splitter to end up at D_1 as the probability of its descendents to end up there.

The gedanken story with a "sleeping pill" explains how the concept of probability can be introduced in the framework of the MWI. We can apply this idea to any quantum experiment with several possible outcomes. The experimenter can associate probability for different outcomes according to the ignorance probability of each of his descendents to obtain this outcome. And the sleeping pill is hardly necessary since in a typical experiment a superposition of macroscopically different states arises before the observer(s) become aware of the result of the experiment.

9. The measure of existence of a world

A believer in the MWI can define a *measure of existence of a world*, the concept which yields his subjective notion of probability. The measure of existence of a world is the square of the magnitude of the coefficient of this world in the decomposition of the state of the Universe into the sum of orthogonal states (worlds). *The probability postulate* of the MWI is: if a world with a measure μ splits into several worlds then the probability (in the sense above) for a sentient being to find itself in a world with measure μ_i (one of these several worlds) is equal to μ_i/μ. See Lockwood (1989, pp. 230–232) for a pictorial explanation of this rule. Consider, for example, a world with measure of existence μ, in which a neutron enters the beam splitter shown in Figure 1. Assume that the operation of the beam splitter is described by equation (7). Then the measure of existence of the world in which the neutron reaches detector D_1 equals $\mu|\alpha|^2$, and, therefore, the probability for the neutron to find itself in D_1 is $\mu|\alpha|^2/\mu = |\alpha|^2$.

During the period that a neutron evolves as a single LWP, its measure of existence has no physical manifestation. All physical parameters, such as mass, spin, magnetic moment etc., are independent of the measure of existence. A neutron with a tiny measure of existence moves (and feels) exactly like one with measure 1. The measure of existence manifests itself only in processes in which splitting of the world takes place (in the standard interpretation it corresponds to the situations in which a collapse occurs). The relative measures of existence of the worlds into which the world splits provide a concept of probability.

I believe that the argument above, explaining how the measure of existence of future worlds yields a probability concept, is enough to justify introducing the concept of "measure of existence". However, even the measure of existence of present worlds has physical meaning. What is the "advantage" of being in a world with large measure of existence? When the neutron (i.e. LWP) evolves without splitting, the other worlds cannot interfere. When it splits into two in a beam splitter, the other worlds usually do not interfere either, but they can! Consider the neutron moving inside the upper arm of the interferometer (Figure 3) and assume that its measure of existence equals 1/2. Being unaware of its "twin" in the bottom arm, it calculates equal probabilities for reaching detectors D_1 and D_2. But, the neutron's God, namely the experimenter, makes use of the other neutron world and *changes* the probabilities completely. He arranges destructive interference of the neutron's waves coming toward D_2, see Figure 3. If, however, the neutron in the upper arm has measure of existence $\mu \simeq 1$ (if the beam splitter S_1 is replaced by the one which transmits most of the wave), then nobody, not even God, can significantly change the quantum probabilities because the amplitude of the wave corresponding to the other world is too small. More generally, when the measure of existence is less than or equal to 1/2, the God can change probabilities of further splitting completely; when it is greater than 1/2, only partially, and when it is equal to 1 the God cannot change the probabilities at all. Of course, even for neutrons, experimenters have to work hard to change such probabilities. A similar experiment involving human beings (I discuss one in the next section) would be astronomically difficult. We have no indication that any God (superintelligence from another planet) plays such a game with us.

10. The MWI as a universal theory

According to the MWI the Universe, everything that exists, is characterized by a single quantum state, the State. The time evolution of the State is completely deterministic (given by Schrödinger's equation). Essentially, the Universe *is* the State. The world, as we commonly understand it through our experience, corresponds to a tiny part of this State, and we, to some fragment of this part. What specifies and defines *us* is the configuration, the shape of the fragment of the state corresponding to our world.

The State $|\Psi\rangle$ can be decomposed into a superposition of orthogonal states $|\psi_i\rangle$ corresponding to different worlds:

$$|\Psi\rangle = \sum_i \alpha_i |\psi_i\rangle \tag{11}$$

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 the MWI is not part of the mathematical theory, but a subjective entity connected to the 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 interpret the speculation of Wigner (1962) about the collapse caused by the consciousness of the observer, i.e. to understand it not in a literal sense, that there is a law according to which consciousness affects physical processes, but instead, in the sense that the conscious observer defines the basis of decomposition of the Universe into the worlds. Thus, one experimenter's world encompasses two (sentient) neutron worlds. I analyze this "observer decomposition" in Section 13.

The coefficients of the equation (11) yield measures of existence of different worlds. The measure of existence of the world $|\psi_i\rangle$ is $|\alpha_i|^2$. Although we do not experience it directly, I can, as above, discuss two manifestations of the measure of existence. The first manifestation is for the future worlds. Every time there is a situation in which the world splits it is important for a believer in the MWI to know the relative measures of existence of the splitted worlds. If asked, he will bet according to these numbers. In particular, for the experiment described in Figure 1 in which the neutron passes through a 10%–90% beam splitter, he will bet 1 : 9 for the neutron reaching corresponding detectors. He understands that he has an illusion of corresponding probabilities even though no random processes take place in the Universe. In fact, this behavior of the believer in the MWI will be identical to the (normal) behavior of a believer in the collapse governed by the Born probability rule. The second manifestation, which can be seen only in a gedanken experiment, is for the measures of existence of the present worlds. I will show that in a certain situation we should behave differently just because of the different values of the measure of existence of corresponding worlds.

Let us assume that tomorrow a "superman" lands on Earth. He is far more advanced in technology than we are, and he shows us that he can perform interference experiments with macroscopic bodies. He resurrects Schrödinger cats, "undoes" measurements like those I describe in Section 11 below (showing that no collapse takes place and that the MWI is correct), etc. He also convinces us that we can rely on his word. Then he offers me a bet, say 1 : 1, that the neutron which passes through a 10%–90% beam splitter as above will end up in detector D_1 (corresponding to 10% probability calculated naively). He promises not to touch *this* neutron, i.e. the neutron coming 45° up. Now it is important for my decision whether to accept or to reject the bet to know my *present* measure of existence. I remember that after the superman's landing I performed a quantum experiment and obtained a very improbable result. This means, that the measure of existence of my world is very small relative to that in which there is another Lev Vaidman to whom the superman with his super-technology also has an access. Thus, the superman can, in principle, change the state of my twin in this other world (including the twin's memory) making it identical to that of mine and send in the other world the neutron 45° from the top, arranging, via interference of the two worlds, zero probability for the detection by detector D_2 (which had 90% probability without the actions of the superman). So, in that case I *should not* take the bet. If, however, I know that I have a large measure of existence compared with twins with which the superman might play, then I *should* take the bet, since the superman, in spite of his unlimited technological power, cannot change significantly the probabilities of the measurement outcomes (the measures of existence of corresponding worlds).

11. Test of the MWI

A widespread misconception about the MWI is that its predictions are identical to the predictions of the standard approach (e.g. De Witt, 1970). Let me describe here the design of an experiment that distinguishes between the MWI and the standard (collapse) approach (see also Deutsch (1986) and Lockwood (1989, p. 223). The measurement process of the experiment illustrated in Figure 1, including the observation of its result by an experimenter, can be described (if the MWI is a correct theory) by Schrödinger's equation with a certain Hamiltonian. A "superman" could build a device with a "time reversal" Hamiltonian which could "undo" the measurement. The "time reversal" Hamiltonian would erase the memory of the experimenter, the detectors would return to the "ready" state, and the neutron would return to its original place, i.e. the neutron's source. At this stage we replace the source of the neutron by a detector. If no collapse takes place, the detector will detect the neutron with probability 1. The neutron in its "reverse" motion arrives at the beam splitter from two directions and, as in the neutron interference experiment (Figure 3), continues in a single direction toward the detector. If, however, the collapse takes place at some stage during the measuring procedure—say, when the experimenter looks at the detectors—then the neutron in its "reverse" motion arrives at the beam splitter only from one direction. 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, the MWI will be confirmed if the neutron is always detected by the detector, and it will be refuted if the neutron is detected in only 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 a human observer is also a reasonable test of the MWI. With progress in technology, we can get closer and closer to a decisive experiment.

12. How many worlds?

Healey (1984) and many others became opponents of the MWI by puzzling over the question of how many worlds there are. The number of worlds is huge, and it is not clear how to define it rigorously. Nevertheless, I do not see this as a serious problem, 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 has 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 expectation 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, I define that the world does not exist. I do not know the State. Therefore, I do not know if any particular world exists. I do know that the world in which I wrote this paper exists. I also have knowledge about quantum experiments with different possible outcomes which were performed in the past. 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. (I disregard improbable situations in which the worlds recombine.) I tend to believe that even without special designs of quantum-type experiments, there are numerous processes which split the worlds. This question can be resolved by careful analysis using the standard approach. Every time we encounter a situation in which, according to the standard approach, collapse must take place, there splitting in fact takes place; and the ambiguity connected with the stage at which collapse occurs corresponds to the subjective nature of the concept of world. While this ambiguity represents a very serious conceptual difficulty of the collapse theories, it is not a serious problem in the MWI. The collapse as a physical process should not be vaguely defined, while the vagueness of the concept of a conscious being is more of an advantage than a problem.

Recently Leslie (1996) analyzed another difficulty related to counting worlds. He applied Carter's (1983) "doomsday argument" to a naive version of the MWI and pointed out that "all except a vanishingly tiny proportion of one's versions would come into existence near one's death, outweighing all apparent evidence that death was not imminent". The way out of this paradox is attaching larger probability weights to branches with larger quantum amplitudes. Leslie thought that the fact that all Everett's branches are "equally real" prevents this way (but he noted that this might not be true). It seems to me that my analysis of "measure of existence of a world" yields exactly this resolution of Carter's doomsday paradox.

13. Locality of the preferred basis

Let me sketch a conjecture about the evolution of sentient observers with local senses such as we possess. Consciousness is a collection of thoughts. Thoughts are representations of causal chains of events. Events are describable in terms of observer's experiences. The experiences are obtained through the senses in a process explainable by physical interactions. Physical interactions are local. These are the reasons why causal chains represented by our thoughts consist of *local* events.

Applying this conjecture to our example, the neutron, "created in the human image", can understand local events such as hitting a mirror, while it cannot comprehend the experience of being in two places simultaneously. The neutron distinguishes between local worlds given by equation (5) and cannot distinguish among orthogonal nonlocal states as in equation (6).

Physics explains why an observer who "thinks" in the concepts of nonlocal superpositions is not favored by evolution. Imagine an observer who can distinguish between two nonlocal orthogonal states of a macroscopic 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 of Figure 1 is

$$1/\sqrt{2}(|in\ \mathrm{D}_1\rangle|in\rangle_{\mathrm{D}_1}|r\rangle_{\mathrm{D}_2} + |in\ \mathrm{D}_2\rangle|r\rangle_{\mathrm{D}_1}|in\rangle_{\mathrm{D}_2}), \tag{12a}$$

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

$$1/\sqrt{2}(|in\ \mathrm{D}_1\rangle|in\rangle_{\mathrm{D}_1}|r\rangle_{\mathrm{D}_2} - |in\ \mathrm{D}_2\rangle|r\rangle_{\mathrm{D}_1}|in\rangle_{\mathrm{D}_2}), \tag{12b}$$

he makes a record " − ". However, these records will not be helpful because through local interactions with the environment the system consisting of the neutron and two detectors will in both cases soon cease to be in a pure quantum state. The system will be described by a mixture with equal probability of states (12a) and (12b). Compare this with an observer who makes a local measurement that distinguishes between states

$$|in\ \mathrm{D}_1\rangle|in\rangle_{\mathrm{D}_1}|r\rangle_{\mathrm{D}_2} \tag{13a}$$

and

$$|in\ \mathrm{D}_2\rangle|r\rangle_{\mathrm{D}_1}|in\rangle_{\mathrm{D}_2}. \tag{13b}$$

The records of the latter will be accurate even after the interaction with the environment. Thus, the sentient being who thinks in terms of *local* properties has an evolutionary advantage due to the stability of local states (such as (13a) and (13b)). I believe that the decomposition of the Universe into sensible worlds (11) is, essentially, unique. The decomposition, clearly, might differ due to coarse or fine graining, but to have essentially different decompositions would mean having a multi-meaning Escher-type picture of the whole Universe continuously evolving in time.

14. God does not play dice

The statement "God does not play dice" is probably the most famous objection Einstein had 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 a probability of genuinely unpredictable outcomes. Quantum events are such that even God (or infinitely advanced technology) cannot predict them. Unless God has some nonlocal features, which is in conflict with Einstein's even more sacred principle, God cannot predict the outcomes of some quantum measurements performed on a simple system of two spin-1/2 particles.

The MWI solves the difficulty of the genuinely random Universe. God does not play dice. Everything is deterministic from the point of view of God. Everything evolves in time according to Schrödinger's equation. At the same time, there is an explanation of why for *us* there is genuine unpredictability when a quantum measurement is performed. Ballentine (1975), however, claims that God does play dice even in the framework of the MWI. He plays dice when he assigns the "me" whom I know to a particular world. However, at least in my version of the MWI, God does not and *cannot* do it. I am in a privileged position relative to an external observer, including God, in my ability to identify myself without specifying the world in which I am. God can identify me only by the world in which I am. Therefore, God cannot assign the "me" whom I know to a given world, and he cannot define an objective *probability* for the "me" whom I know ending up in a particular world. Compare with the discussion of the neutron with a sleeping pill and an experimenter in Section 8.

The concept of probability in the MWI is very different from our usual probability. Previously, we always used the concept of probability when one of several possibilities would take place; but according to the MWI *all* these possibilities are realized in the Universe. I believe, however, that I have succeeded in introducing a concept of subjective probability for sentient beings in each separate world, while leaving the whole Universe deterministic. The probability postulate—probability is proportional to the measure of existence—explains the only thing which, I think, requires an explanation: an experimental fact about the consistency of frequencies of outcomes of quantum measurements (performed in *our* world) with statistical predictions of standard quantum theory. Indeed, the sum of measures of existence of all such worlds is overwhelmingly larger than the sum of measures of existence of worlds in which the frequencies of the quantum measurements differ significantly from those predicted by the quantum theory.

15. Why the MWI?

The crucial argument in favor of the MWI is that in this theory there is no collapse to be explained. The bad features of the collapse cannot be overestimated. Gottfried's comment (1989) that "The reduction [collapse] postulate is an ugly scar on what would be a beautiful theory if it could be removed" represents the feelings of many physicists. There is no clue as to when exactly the collapse occurs. If it does occur, it seems impossible to avoid contradictions with special relativity. In spite of persistent efforts in the last half century, there is no satisfactory physical explanation of the collapse.

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

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

It seems that the MWI can be extended to the relativistic domain because all paradoxes of superluminal changes disappear with the removal of the collapse. For discussion of quantum nonlocality in the framework of the MWI see Vaidman (1994).

The MWI yields a novel basis for the investigation of the relation between mind and matter. According to the MWI, a human being *is* a wave function which is a part of a quantum state which *is* the world, which in turn is one term in the superposition of many quantum states which comprise the State, which *is* the Universe.

Although one does not have to believe in the MWI in order to design a machine which employs quantum interference on a macroscopic scale, it is clearly more natural to discuss these possibilities when one does not need to worry about "miraculous" collapses, but only about quantum correlations described by Schrödinger's equation. It is not a coincidence that the pioneer of "quantum parallel processing" is an enthusiastic proponent of the MWI—Deutsch (1985). While it is hopeless to reach the "other" worlds which are already splitted from "our" world, it is feasible to create several worlds carefully and to reunite them later. This is, essentially, the subject of intensive current research of building a *quantum computer* which splits to make many different calculations in parallel and reunites to give the final result.

I have one more reason to be enthusiastic about the MWI. It helps me to see and understand novel features of quantum mechanics. Thinking in terms of the MWI was especially fruitful in recent work by Elitzur and myself (Elitzur & Vaidman, 1993).

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Notes

1. Space limitation does not allow a comparative analysis of alternatives. An extended version of this paper which discusses some other interpretations and includes many references can be found in preprint form (Vaidman, 1996).

2. The word "schizophrenia" does not describe precisely the neutron's experience, but I cannot find a better alternative. The difficulty in language is not surprising since, before quantum mechanics, humans had no reason to discuss this kind of situation.
3. Albert (1987) pointed out another interesting "privilege" of an observer in comparison with external systems: the observer is the *only* one in a position to know certain facts about himself.

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