ON SCHIZOPHRENIC EXPERIENCES OF THE NEUTRON OR WHY WE SHOULD BELIEVE IN THE 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.

– Bertrand Russell

1. Introduction

There are many interpretations of quantum mechanics, and new ones continue to appear. The Many-Worlds Interpretation (MWI) introduced by Everett (1957) impresses me as 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 of other interpretations are more serious. However, the scope of this paper does not allow a comparative analysis of all alternatives, and my main purpose here is to present my version of MWI, to explain why I believe it is true, and to answer some common criticisms of MWI.

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 fairly well. Indeed, according to MWI (and contrary to the standard approach) there are *many worlds* of the sort we call in everyday life "the world". And although 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 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. I shall argue in what follows that it also implies the existence of many worlds. The purpose of addition of the collapse postulate, which represents the difference between MWI and the standard approach,[1] 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

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[1]In fact, there are several other interpretations without collapse. I consider these interpretations to be variations of MWI. Indeed, if there is no collapse then the states corresponding to all worlds of MWI exist. See more in Section 15.

advantage of 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 I emphasize that the validity of 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 conscious neutron passing through the interferometer *must* have schizophrenic experiences. In Section 4, I introduce a neutron's MWI and explain how it solves the problem of the neutron's schizophrenia. In Sections 5-10, I continue the discussion of MWI using the example of the neutron interferometer. In Section 11 I present, and in sections 12-14 I discuss, the MWI of the Universe. Section 15 is devoted to the *causal interpretation* (Bohm, 1952) which is probably the best alternative to MWI. In Section 16, I summarize the arguments in favor of MWI. Section 17 is an addition to the paper in which I reflect on recent symposium on the Many-Minds Interpretation of Lockwood (1996).

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.

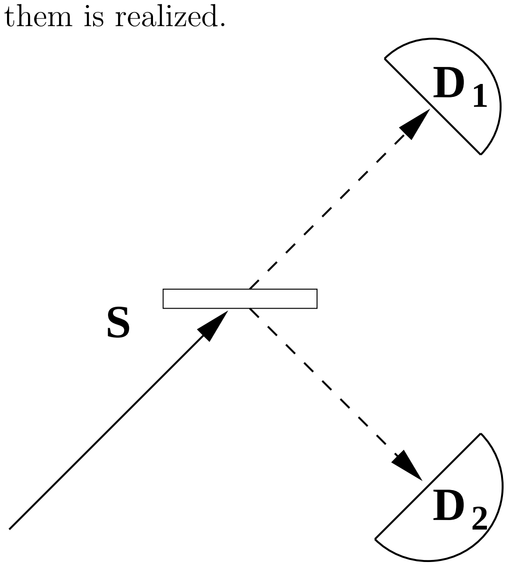

Figure 1: The neutron beam splitter.

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 the his 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, 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, *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.

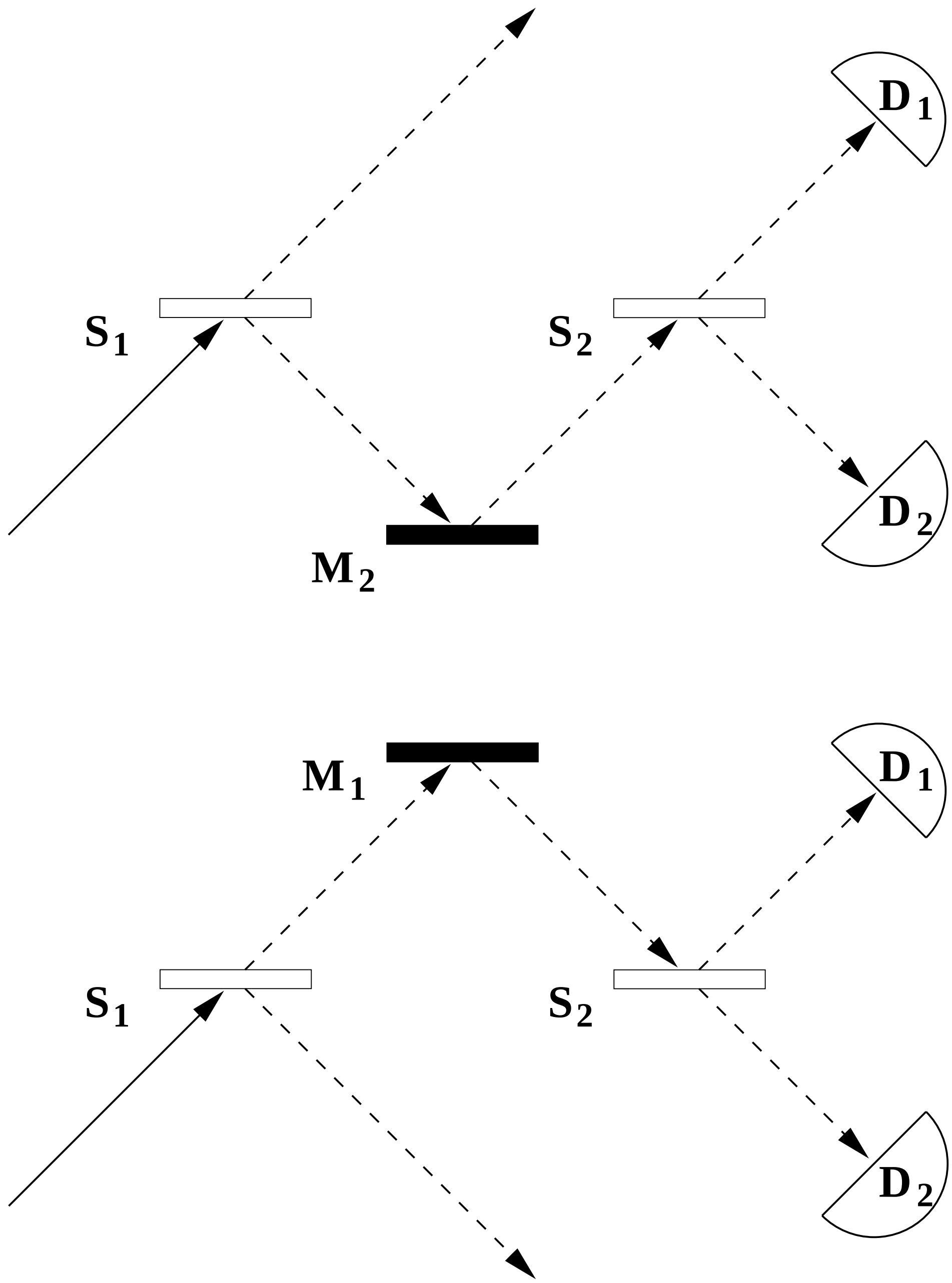

Figure 2: Two arrangements of neutron beam splitters and a neutron mirror.

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 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 this is the correct description by considering results of the experiments with a mirror and two beam splitters in 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). Taking the assumption of the previous section it is impossible to 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.

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 does not show what is expected! *All* the neutrons are detected by detector D_1.[2]

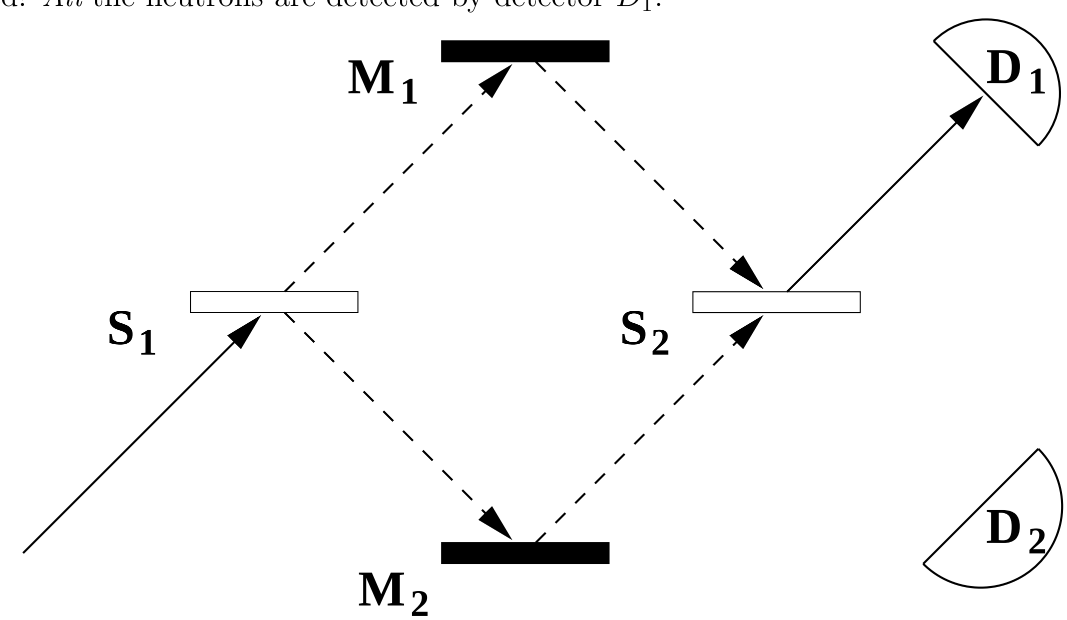

Figure 3: The neutron interferometer.

We cannot explain the experimental results by the picture of 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 therefore have schizophrenic experiences.[3]

[2]Here (and in a few places below) I sacrifice rigor for simplicity by omitting technical details. A precise statement here is that one *can tune* the interferometer such that all neutrons are detected by D_1.

[3] 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.

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 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, kicked by mirror M_1 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 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 in 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 the result 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 twin-neutrons by placing an absorption screen before mirror M_1 (M_2).

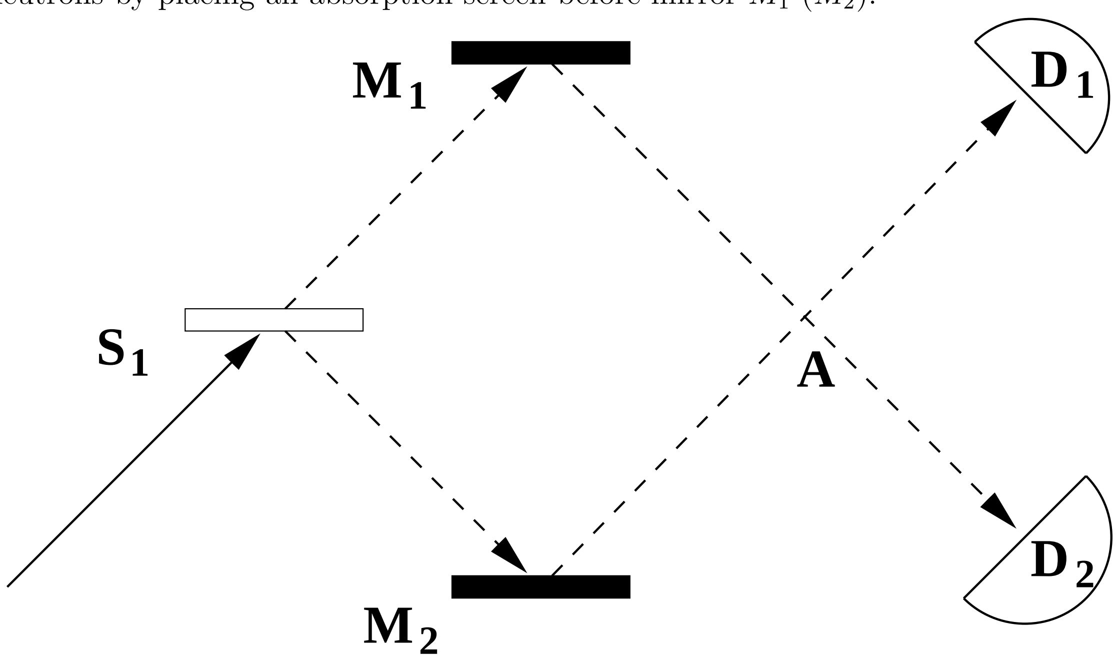

Figure 4: The neutron interferometer without second beam splitter.

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? Quantum theory tells us that the neutron *cannot* retain memories about which trajectory it took (in which world it "lived"). 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 (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.

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 the 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? In fact, in any real situation there is no exact answer to this question. (Zero uncertainty in the position requires infinite energy.) 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. (Macroscopic bodies are also described by LWPs. Even a leading theory of collapse, see Ghirardi and Pearle (1990), considers reduction of the quantum states of macroscopic bodies only into LWPs.) 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 becomes again 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 demonstrate now this quantum interference effect using some formulas.

I designate by $|up\rangle$ and $|down\rangle$ the states of the neutron moving 45^0 up and 45^0 down respectively (see Figures 1-4). After the passage through a beam splitter the state of the neutron changes as follows:

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

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

The action of mirror M_1 is

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

and of mirror M_2,

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

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:

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

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 Eq. (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:

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

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. 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 chose this particular one? Why not, for example, take an alternative decomposition of the same state:

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

But the two components in Eq. (6) do not correspond to "neutron worlds". Indeed, I have made an assumption that neutrons are similar to us, i.e., a sentient neutron is not schizophrenic as it would have to be in the worlds corresponding to $1/\sqrt{8}((1+i)|up\rangle + (1-i)|down\rangle)$ 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 at every moment. It is possible to decompose each term in Eq. (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.

I want to stress that "world" is not a physical concept. It is defined by the conscious mind of the observer. "Physics" does not prefer the decomposition into LWPs. It is the fact that the observer has local senses that explains why an evolution of a LWP corresponds to a definite chain of events which he perceives, a story which defines a particular world. See more in Sections 13 and 17.

7. The Concept of Probability of a Believer in MWI

Let me now 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 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 Eq. (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

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

Quantum theory yields for the neutron, in this case, the probability $|\alpha|^2$ to be found in D_1 and the probability $|\beta|^2$ to be found in D_2.

It is more difficult to define a concept of probability for those experimenters and those neutrons who know 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 just 1. *We* cannot assign any other number to this probability, but the neutron *can.* 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 using its location, while each sentient neutron does not need information to identify itself.[4] 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 converts 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 ancestors to end up there.

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

8. The Measure of Existence of a World

A believer in 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 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 time 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 (feels) exactly as 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 provides 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

[4] 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.

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. 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. 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. Even for neutrons, experimentalists have to work hard to change such probabilities. A similar experiment involving human beings (I discuss it in Section 11) would be astronomically difficult. We have no indication that any god (superintelligence from another planet) plays such a game with us.

9. 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 Many-Worlds Interpretation of quantum mechanics, in spite of its 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 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 MWI and the standard approach let us consider a neutron passing through a beam splitter with action described by equation (7) and detected by detectors D_1 and D_2 (Figure 1). According to MWI, the description of this process is:

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

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 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:

$$\alpha|in\ D_1\rangle|in\rangle_{D_1}|r\rangle_{D_2} + \beta|inD_2\rangle|r\rangle_{D_1}|in\rangle_{D_2} \rightarrow$$
$$\rightarrow \begin{cases} |in\ D_1\rangle|in\rangle_{D_1}|r\rangle_{D_2} & \text{(probability } |\alpha|^2) \quad \text{or} \\ |in\ D_2\rangle|r\rangle_{D_1}|in\rangle_{D_2} & \text{(probability } |\beta|^2) \end{cases} \quad (9)$$

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:

$$\Big(\alpha|in\ D_1\rangle|in\rangle_{D_1}|r\rangle_{D_2} + \beta|in\ D_2\rangle|r\rangle_{D_1}|in\rangle_{D_2}\Big)\ |r\rangle_E \rightarrow$$
$$\rightarrow \alpha|in\ D_1\rangle|in\rangle_{D_1}|r\rangle_{D_2}|see\ D_1\ 'in',\ D_2\ 'r'\rangle_E$$
$$+\ \beta|in\ D_2\rangle|r\rangle_{D_1}|in\rangle_{D_2})|see\ D_1\ 'r',\ D_2\ 'in'\rangle_E \qquad (10)$$

where $|see\ D_1\ 'in',\ D_2\ 'r'\rangle_E$ 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. It might be that their measures of existence are different, i.e., in some sense, there is "more" of one world than of the other. However, I still should not say that this 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.

10. Test of MWI

A widespread misconception about 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 MWI and 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 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 Eq. (1)). In this case the probability of detecting the neutron is equal to 1/2. Thus, 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 MWI. If the detector is microscopic, then it is even feasible now to design the device which undoes the interaction between the neutron and the detectors. With progress in technology, we can get closer and closer to a decisive experiment. A new experimental field, two-particle interferometry (Horne, Shimony and Zeilinger 1989), is a significant step toward this goal. While in the case of a neutron interferometer, the two worlds which were made differed only with respect to the trajectory of a *single* neutron, now the worlds which interfere with each other differ with respect to the trajectories of *two* particles.

11. 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 (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. I see remote support for this picture in recent work of Redhead and Teller (1992) denying individuability of identical particles. Thus, in particular, we are not to label the electrons, the protons, etc. out of which *we* are made. 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 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 understand speculation of Wigner (1962) about the collapse caused by the consciousness of the observer, but not in a literal sense, i.e., that there is a law according to which consciousness affects physical processes. Instead, 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 (see also Ben-Dov, 1990).

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 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, say $10\% - 90\%$ beam splitter he will bet 1:9 for the neutron reaching corresponding detectors. He understands that he has an illusion of corresponding probabilities even so no random process take place in the Universe. In fact, this behavior of the believer in MWI will be identical to a (normal) behavior of a believer in the collapse governed by 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" will land on Earth. He is far more advanced in technology than we are, and he will show to us that he can perform interference experiments with macroscopic bodies. He will resurrect Schrödinger cats, "undo" measurements described in Section 10 (showing that no collapse takes place and that MWI is correct) etc. He also will convince us that we can rely on his word. Then he will offer 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 will promise not to touch *this* neutron, i.e., the neutron coming 45^0 up. Now it is important for my decision of accepting or rejecting 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 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 45^0 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 compare to 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) .

12. How Many Worlds?

Healey (1984) and many others became opponents of MWI trying to answer 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 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 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 possible different 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, in the standard approach, collapse must take place, splitting takes place; and the ambiguity connected with the stage at which collapse occurs corresponds to the subjective nature of the concept of world.[5] There are very many worlds from the perspective of human beings, although not as

[5] 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 framework of

many as in the modal realism approach of Lewis (1986) in which *every* logically possible world exists. See a comparative analysis by Skyrms (1976).

13. Locality of the Preferred Basis

Let me sketch a conjecture about a theory of 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. The neutron, "created" here "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 Eq. (5) and cannot distinguish among orthogonal nonlocal states as in Eq. (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

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

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

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

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 with an observer who makes a local measurement that distinguishes between states

$$|in\ D_1\rangle|in\rangle_{D_1}|r\rangle_{D_2} \qquad (13a)$$

and

$$|in\ D_2\rangle|r\rangle_{D_1}|in\rangle_{D_2}. \qquad (13a)$$

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)). An extensive research, led by Zurek (1993), of the role of the environment in the measuring process shows the stability of local events in the causal chain of a human observer. 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.

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concepts of conscious beings might have a lot of freedom.

Recently Saunders (1993), equipped with heavy formalism of *decoherent histories* developed by Gell-Mann and Hartle (1990), investigated (in the framework of MWI) a model of "evolutionary adaptation". It has the above mentioned elements of locality and stability. Although I do not necessarily accept his model, I am certainly encouraged by his conclusion: "These arguments [his arguments for evolutionary adaptation] are qualitative, but it seems that there is no difficulty in principle in construction of more detailed models."

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. Bell (1964) proved that 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 MWI. He plays dice when he assigns the "me" whom I know to a particular world. However, at least in my version of 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 7.

Very recently Page (1995) supported this approach by arguing that "probabilism is a myth". He developed a "sensible quantum mechanics", a variant of MWI in a "many-perceptions" framework. Although it has some resemblance with the many-minds interpretation of Albert and Lower (1988), the latter is different: the "minds" do evolve probabilistically. See also a thorough philosophical analysis of various alternatives by Butterfield (1995).

The concept of probability in 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 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. (The latter worlds also exist, but in these worlds sentient beings have no reason to believe that the quantum theory is correct.)

Up to the present, there continues an extensive debate (see Kent, 1990 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 that the probability of result i is 0 when $|\alpha_i|^2 = 0$ and 1 when $|\alpha_i|^2 = 1$ (see Eq. (11)) it *follows* that the probability for the result i is equal to $|\alpha_i|^2$ for *any* value of α_i. I agree with the opponents of MWI that the assumption of the existence of many worlds does not help to derive the quantum law of probability. This debate has reflected badly on MWI. Failure of MWI to be useful in deriving the quantum law of probability is frequently - but wrongly - considered to be a proof of its inadequacy. In fact, no other interpretation is better in this respect.

15. The Causal Interpretation

As a physical theory, the MWI is more economical than any other quantum theory without collapse. The no collapse assumption invariably leads to the existence of the State of the Universe with all its "branches" corresponding to all innumerable worlds of MWI. So all the complexity of of MWI is there and, in addition, there is something else. Let me, however, touch here one other leading non-collapse interpretation.

A very interesting non-collapse theory is the "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 the values of the wave function in the immediate vicinity (in configuration space) of the point according to a simple equation (especially simple in Bell's version of the theory).

Proponents of the causal interpretation frequently consider both the wave function and the Bohmian particle (the point) as "physically real". I, however, find the most fruitful approach to the Bohm theory the interpretation according to which only *the point* corresponds to "reality", while the wave function is a secondary entity, whose purpose is to be a "pilot" of the point. Only in this way I can see how the causal interpretation describes a single "real" world.

The paradoxes of non-relativistic quantum mechanics 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 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. (The argument of Bell for the unpredictability of spin measurements performed on a certain pair of spin-1/2 particles is solved explicitly according to the Bohr's vision: the outcome of a spin measurement is certain only when we specify the measuring device we use.)

So it seems that the causal interpretation has all the good properties of MWI and it has only a single world: surely a desirable feature. I, however, do not consider it preferable to MWI. Besides the main technical problem, the lack of reasonable generalization to relativistic domain I want to mention two other points.

The first point is a peculiar and, in my opinion, unfortunate feature of the causal interpretation which has been understood only recently. Bell (1980) pointed out that in some situations the Bohm trajectory is very different from what we would naively think, and moreover, Englert *et al.* (1992), Brown *et al.* (1995), and Aharonov and Vaidman (1996) have shown that it might be different from what an apparently good measuring device would show. Consider the experiment described in Figure 4. A single neutron entered the beam splitter S_1 and has been detected by, say, detector D_1. Then, we would say that its trajectory is $S_1M_2D_1$. But the Bohm trajectory (called by Englert *et al.*(1992) "surrealistic trajectory") in this case is $S_1M_1AD_1$. The neutron changes the direction of its motion at point A in spite of the fact that no beam splitter is there. Moreover, if we try to observe the trajectory of the neutron we might be "fooled" by our measuring apparatus. Let us assume that the experiment is performed in a special "bubble chamber", such that the mechanism of creation a bubble by the neutron is such that the neutron changes an internal state of some atom and then the atom slowly creates the bubble. This process is slow enough that during the time the neutron passes from the beam splitter S_1 till the time it reaches the intersection point of the two possible trajectories A (see Figure 5) the wave function of the excited atom does not change significantly its spatial distribution. In this case, the Bohm trajectory is again $S_1M_1AD_1$ while the bubbles, developed after the neutron passage, will show (naively expected) $S_1M_2D_1$.

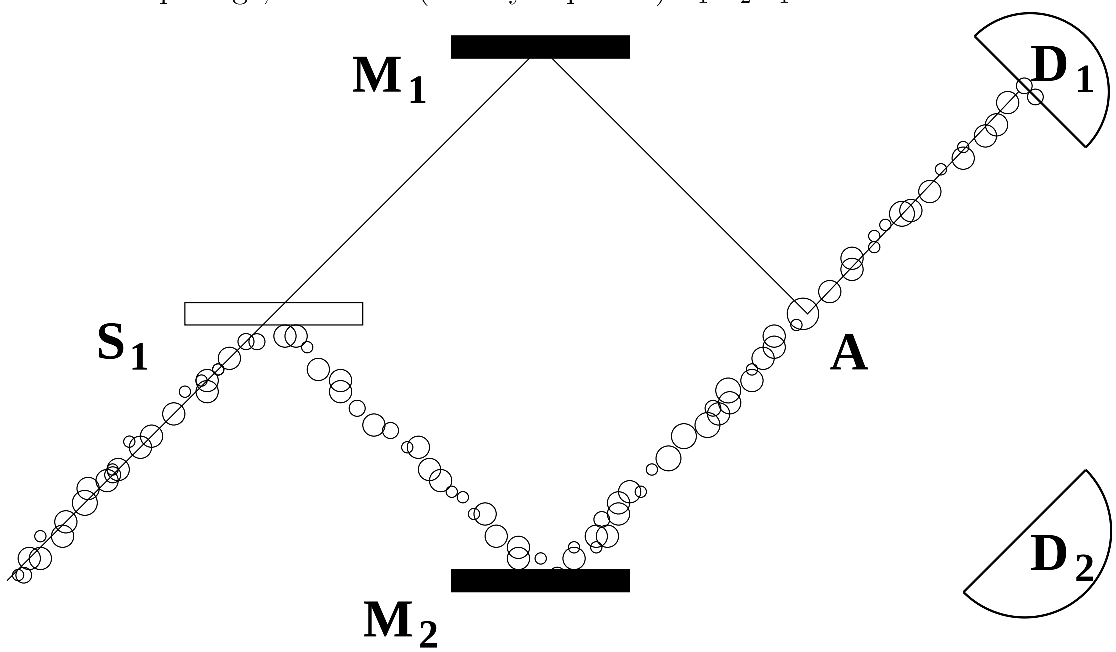

Figure 5: The neutron interferometer without second beam splitter in a bubble chamber.

The last point is probably the most important argument against accepting the causal interpretation or any other non-collapse interpretation which has some additional elements. I do not see that these interpretations really get rid of all but one world. If a component of the quantum state of the Universe, 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? How do *I* know that I am not this "empty" wave?

16. Why MWI?

The crucial argument in favor of MWI is that in this theory there is no collapse to be explained. 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", Gottfried's phrase (1989), represents the feeling of many physicists. There is no clue 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. Extremely divergent proposals for the cause of the collapse, such as consciousness (Wigner, 1962), gravitation (Penrose, 1994, pp.335-347), new genuine random processes (Ghirardi and Pearle, 1990), etc. indicate the difficulties in the task 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 want to believe, that at least in principle, Science can explain everything.

Most physicists who favor MWI do so because it allows them to consider the quantum state of the Universe, the basic concept in quantum cosmology (e.g. Clarke, 1974). 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.

Although nobody has done it explicitly, it seems that 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 MWI see Vaidman (1994).

MWI yields a novel basis for the investigation of the relation between mind and matter. According to 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.

It might be worthwhile to make an attempt to learn about the "other" worlds by investigating records of quantum measurement-type interactions. Thus we will obtain some information about the whole Universe, beyond our subjective world. This information might lead to better understanding of the problems of evolution.

MWI can greatly influence the ongoing discussion (see Healey, 1992) of causation, EPR correlations etc. It provides a deterministic physical theory without nonlocal interactions.

Although one does not have to believe in 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 MWI – Deutsch (1985). While it is hopeless to reach the "other" worlds which are already split from "our" world, it is feasible to create several worlds carefully and to reunite them later. This is, essentially, the subject of current intensive research of building a *quantum computer* which splits to make many different calculations in parallel and reunites to give the final result. Recently Shor (1994) has shown that quantum computer can solve some important problems significantly faster than any existing algorithm of classical computation.

I have one more reason to be enthusiastic about MWI (see Vaidman, 1994). It helps me to see and understand novel features of quantum mechanics. Thinking in terms of MWI was especially fruitful in recent work by Elitzur and myself (1993).

17. Reflections on the 'Many Minds' Interpretation

While I was correcting the manuscript according to suggestions of the referees British Journal for the Philosophy of Science has published an enlightening Symposium on 'Many Minds' Interpretations of Quantum Mechanics. The issues discussed in the Symposium are very closely related to what I have described above and I believe that my brief reflections on the Symposium will help to understand my MWI and will avoid misunderstandings due to different terminology.

My MWI is much more close to the Many Minds Interpretation (MMI) of Lockwood (1996) than to the MWI he refers to. The latter seems to be inspired by De Witt (1970) and I have criticized it myself (see Sec. 10). Papineau's (1996) illuminating analysis of "what it *would be like* to have a superposed brain" in the framework of MMI corresponds exactly to my understanding of MWI; and I am ready to sign under Lockwood sentence (1996, p.170): "A many minds theory, as I understand it, is a theory which takes completely at face value the account which unitary quantum mechanics gives of the physical world and its evolution over time" with the only change of "many minds" to "many worlds".

Indeed, I believe that the name "Many Worlds" is more appropriate; I defend it in Section 1. I also find support to this choice in the Symposium: Deutsch (1996), apart from analyzing strong (although indirect) evidences for existence of many worlds (which he names "universes"), gives personal testimony for Everett's similar view.

Beyond semantics, I do not think that Lockwood's concept of "Mind" is as important and fruitful as he suggests. What corresponds to our everyday experience is Lockwood's "mind". The "Mind" is the concept which is relevant only for "god" (infinitely advanced technology). But even god might find this concept not very clear because of the ambiguity related to the birth of Mind: the mother might be in a superposition of being pregnant for different times and from different fathers.

Another argument in favor of "world" relative to "mind" (or "Mind") is that in the many worlds picture we are not forced to accept "radicalism" discussed by Butterfield (1996) according to which "unobserved macroscopic world can be very indefinite, even within a branch". In my MWI a world is a "sensible story". Thus, if we are not ready to consider stars (even those we cannot see now) being in a superposition of states corresponding to macroscopically different locations, we can always choose an appropriate basis such that we will have stable classical-type stories. We also might discuss many worlds at far past (or far future?!) when no conscious minds were (will be) present by choosing the basis according to understanding pattern of present sentient beings.

However, the main aspect of "mind" – its role for defining *preferred basis* – I see exactly as Lockwood does. As it is stressed in the Symposium by Lockwood, Papineau, Saunders (1996) and others, the preferred basis is not fixed by fundamental physics. The basis is defined by a sentient observer. The fundamental physics, however, due to locality of the basic interactions leads, via *decoherence*, to existence of only certain types of sentient beings. I cannot see any difficulty with this explanation, but in the Symposium I found only cautious appeal to decoherence, see Brown (1996).

Butterfield (1996, p.203) points out that in MWI the preferred basis need not be fixed once and for all and he argues that this is a disadvantage relative, say, to the Bohm theory. I agree that a theory which gives the basis (and even better, a specific choice of the basis vector) is preferable. However, it seems to me that the price for this definiteness is too high and it is not clear that the goal is really achieved: Deutsch (1996), in his discussion of "unoccupied grooves" or 'mindless hulk', has essentially the same position as I do viewing the Bohm theory to be a many-worlds theory.

Probably the closest point between my MWI and Lockwood's MMI is the issue of probability which got a lot of attention in the Symposium. Lockwood (1996, p.182) insists on "the existence of a naturally preferred *measure* ..." which is essentially "the measure of existence of a world" which I introduce. Papineau (1996) reinforces the introduction of such a measure in MMI (MWI) showing that the concept of probability is in no way better if not worse in other theories. Lower and Butterfield, however, argue that such a probabilistic measure requires introducing "persisting minds" which I do not have in my MWI (except for connection through common memories which might yield an answer to Butterfield). Lower (1996, p.230) writes: "it doesn't make any sense on the Instantaneous Mind View speak of the probability of an instantaneous mind at t evolving to exemplify a mental state M at t' since there is no fact of the matter concerning the transtemporal identity of minds". It seems to me that this is exactly the problem I raised and solved in section 7. Lower realized that the key issue for defining the probability measure is "personal identity". The probability of the mind at t to evolve to the mental state M at time t' is defined as an ignorance probability of the ancestors of the mind at (or prior to) time t' to be in the state M. In fact, I believe that this and the gedanken experiment showing physical significance of the measure of existence of the present world (Section 11) are the main novel points I made here. To summarize, in this paper I went beyond mathematical definition of the probability measure: I succeeded to attach the ignorance-probability meaning to the measure of existence of the future worlds and I found a physical meaning for the measure of existence of the present world by designing a gedanken situation in which one should behave differently only because her world has different measure of existence.

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