Chapter 10

The Measurement Problem I: The Orthodox View, Spontaneous Localization, and Worlds and Minds

In this chapter, we begin the consideration of some of the proposed solutions to the measurement problem by looking at von Neumann's and the spontaneous localization theories, both of which deny the universal validity of TDSE. The first introduces the postulate of collapse, thus excluding a part of the measurement process from the range of TSDE; the second alters TDSE altogether by making it non-linear. Finally, we briefly consider Everett's account and some of its spin-offs, all of which deny the observer reliability principle.

10.1 von Neumann's Projection Postulate

Simply put, von Neumann's solution was to deny that TDSE gives a correct account of the whole measurement process. He adopted the principle, now part of standard quantum mechanics, that upon measurement the state vector collapses onto one of the eigenvectors of the operator representing the measured dynamical observable. He was not the originator of the idea. Dirac had already introduced it in 1927 and repeated it in 1930, when he argued that if two position measurements one immediately after the other were to have different returns, then the particle would be detected to have moved in zero time. Dirac then concluded that physical continuity required that the same obtain in the measurements of other observables (Dirac, P., (1958): 36). However, the collapse principle, under the name of *Projection Postulate*, has become associated with von Neumann's name. With collapse, because of EE, the experiment's return value will be the eigenvalue appropriate to the new state of the system. In short, the Projection

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Postulate guarantees that the pointer is out of superposition; then, EE (or better the "eigenvalue if eigenvector" part) guarantees the determinacy of the result because it explains why we get the appropriate eigenvalue as a return.[1]

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One might object that the introduction of the Projection Postulate merely pushes the problem one step back without really solving it unless we can say, at least, *when* (at which link in the measurement chain) collapse takes place. For example, a typical measurement involves the system S on which the measurement is performed, a measuring device D, and an observer W, characterizable in quantum mechanical terms as, say, the combination of the states of the retina, the optical nerve, and the brain. Does collapse occur at the interface of S and (D W) or (S D) and W? von Neumann produced an argument to the effect that it does not matter when in the measuring process the collapse takes place because at the end the measurement returns are the same. In other words, as far as the results of a measurement are concerned, it does not matter where the line between observed and observer system is drawn.

By using a spin-half particle for simplicity, basically, the argument runs as follows. Suppose the particle in state $|\uparrow_x\rangle$, a SGZ in state $|\chi_0\rangle$ (pointer on position 0), and an observer in state $|ready\rangle$ (eyes open, etc.). Let us also assume that D and W are in working order. The whole system starts in state

$$|\Psi\rangle = |ready\rangle \otimes |\chi_0\rangle \otimes \frac{1}{\sqrt{2}}\left(|\uparrow_z\rangle + |\downarrow_z\rangle\right). \qquad (10.1.1)$$

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[1] Von Neumann calls the process ruled by TDSE a "process of type 2", and one ruled by the Projection Postulate a "process of type 1".

Suppose that the collapse takes place when S interacts with D. Then, there is a transition from a superposition (a pure state) to a (proper) mixed state made of two states:

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$$M = \frac{1}{2}\left|ready\right\rangle \otimes \left|\chi_+\right\rangle \otimes \left|\uparrow_z\right\rangle + \frac{1}{2}\left|ready\right\rangle \otimes \left|\chi_-\right\rangle \otimes \left|\downarrow_z\right\rangle. \qquad (10.1.2)$$

Since W is in working order, the mixture will evolve into

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$$M' = \frac{1}{2}\left|believes\uparrow_z\right\rangle \otimes \left|\chi_+\right\rangle \otimes \left|\uparrow_z\right\rangle + \frac{1}{2}\left|believes\uparrow_z\right\rangle \otimes \left|\chi_-\right\rangle \otimes \left|\downarrow_z\right\rangle. \qquad (10.1.3)$$

Here there is no superposition: W is in a determinate state, either believing that the particle's measurement returned $S_z = 1$ *or* believing it returned $S_z = -1$.

Assume now that the collapse occurs when the system S+D interacts with W. Then, first we have the entanglement of S and D and the system evolves into

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$$\left|ready\right\rangle \otimes \frac{1}{\sqrt{2}}\left(\left|\chi_+\right\rangle \otimes \left|\uparrow_z\right\rangle + \left|\chi_-\right\rangle \otimes \left|\downarrow_z\right\rangle\right). \qquad (10.1.4)$$

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When W interacts with S+D, the collapse takes place and we obtain (10.1.2), which will evolve into (10.1.3). Hence, when the collapse takes place is empirically immaterial to the measurement result.

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However, as Barrett has noted, von Neumann's argument does not establish that when the collapse takes place is altogether empirically irrelevant. Indeed, *if* the collapse is taken to represent a physical event it seems safe to assume that when it occurs has empirical consequences. Consider the state of S+D just before W observes the D's pointer. If the collapse takes place when D interacts with S, then S+D is in the (proper) mixed state

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$$N = \frac{1}{2}\left|\chi_+\right\rangle \otimes \left|\uparrow_z\right\rangle + \frac{1}{2}\left|\chi_-\right\rangle \otimes \left|\downarrow_z\right\rangle. \qquad (10.1.5)$$

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By contrast, if the collapse takes place when S+D interacts with W, then S+D is in the superposition state

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\chi_+\rangle \otimes |\uparrow_z\rangle + |\chi_-\rangle \otimes |\downarrow_z\rangle\right). \qquad (10.1.6)$$

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Although it may be practically impossible to set up an experiment distinguishing (10.1.5) and (10.1.6), they are not the same (Barrett, J., A., (1999): 51).

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Interestingly, quantum mechanics *does* provide an answer of sort to the question of when the correlation between the observed quantity and the pointer of the apparatus is established, that is, when (10.1.6) applies. Following Rovelli, let us define an operator

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$$M = \left(|\uparrow_z\rangle \otimes |\chi_+\rangle\right)\left(\langle\chi_+| \otimes \langle\uparrow_z|\right) + \left(|\downarrow_z\rangle \otimes |\chi_-\rangle\right)\left(\langle\chi_-| \otimes \langle\downarrow_z|\right) \qquad (10.1.7)$$

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(Rovelli, C., (1998)). One can verify that

$$\begin{aligned} M\left(|\uparrow_z\rangle \otimes |\chi_+\rangle\right) &= |\uparrow_z\rangle \otimes |\chi_+\rangle \\ M\left(|\downarrow_z\rangle \otimes |\chi_-\rangle\right) &= |\downarrow_z\rangle \otimes |\chi_-\rangle \\ M\left(|\uparrow_z\rangle \otimes |\chi_-\rangle\right) &= 0 \\ M\left(|\downarrow_z\rangle \otimes |\chi_+\rangle\right) &= 0, \end{aligned} \qquad (10.1.8)$$

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and that M is Hermitian on the space of S+D. The physical interpretation of M is clear: if upon measuring M we obtain 1, then there is the appropriate correlation between spin and pointer, otherwise there is not. As we know,

$$\langle M\rangle(t) = \langle\Psi(t)|M|\Psi(t)\rangle. \qquad (10.1.9)$$

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Given (10.1.8), since $\langle M\rangle(t)$ is the sum of all the returns of measurements of M at time t divided by the number of returns, it is also the probability that the appropriate correlation between spin and pointer has happened at time t. In short, there is a quantum mechanical observable capable of telling us when the measurement correlation occurs.

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Three related points should be noted. First, when Ψ is not an eigenvector of $\hat{M}$, *M* still has only two values, 0 and 1, the probability of each return being given by the appropriate expansion coefficient. Consequently, when the correlation between spin and pointer position is not perfect (Ψ is a superposition of eigenvectors of $\hat{M}$), it looks as if the pointer is *not* between + and **-**, but rather at + or at **-** with some probability or other.

Second, and somewhat distressingly, determining *M*'s value is still a quantum mechanical measurement, with all the usual interpretive ambiguities. In particular, barring eigenvector situations, the orthodox interpretation tells us that *M* acquires values only at measurement, with the result that the measurement correlation between spin and pointer position, whose time we are trying to determine, has a time of occurrence only when *M* itself is measured.

Third, it is unclear whether the time at which the measurement correlation occurs is also the time at which measurement (and presumably collapse) occurs. Obviously, measurement correlation does not occur after measurement, but this leaves open the issue of whether it occurs before or contemporaneously with measurement.[2] Moreover, even if one holds that correlation and measurement, and therefore collapse, are contemporaneous, the second point above remains: *M* cannot tell us what we want because it is itself part of the problem.

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[2] We can measure *M*, an operator on S+D space, only from the point of view of another system W that considers S+D one system. From the point of view of W, D has measured S when (10.1.6) occurs. However, from W's point of view, S's state never collapses; only the state of S+D does. These issues play a significant part in Rovelli's Relational Interpretation, of which more later.

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There is a further problem for the Projection Postulate. As both Schrödinger and von Neumann reasonably noted, the interaction between a measuring device and a quantum system is just a physical interaction like any other: all that happens is an energy exchange within the closed system made up of the observed system and the apparatus. This is exactly what TDSE should deal with. In other words, while the Projection Postulate explains the existence and uniqueness of measurement returns, it seems at odds with TDSE. So, why is the linear dynamics suspended when a measurement occurs? Differently put, what is so special about measurement that the standard linear evolution of the state vector is suspended? Even more basically, what constitutes measurement?

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von Neumann's answer is that a measurement involves a chain at one end of which is the quantity being measured and at the other end is the *observing subject*. "Experience only makes statements of this type: an observer has made a certain (subjective) observation; and never like this: a physical quantity has a certain value." Hence, science requires the acceptance of psycho-physical parallelism, the view that it "must be possible to describe the extraphysical process of the subjective perception as if it were in reality in the physical world, i.e., to assign to its parts equivalent physical processes in the objective environment, in ordinary space" (von Neumann, J., (1955): 418-19). In other words, physical science can only deal with the physical counterparts of mental phenomena, while measurement must end in a mental event not reducible to physical events. Hence, there is something in measurement, the mental event corresponding to a certain brain state, which physical science needs but cannot explain.

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Measurement is bound to retain some degree of mystery because it exists at the border between the physical and the mental.[3]

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10.2 Spontaneous Localization

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<#>Verify (18.1.8). [Hint. Set $\Psi_a = |\uparrow_z\rangle \otimes |\chi_+\rangle$; $\Psi_b = |\downarrow_z\rangle \otimes |\chi_-\rangle$; $\Psi_c = |\uparrow_z\rangle \otimes |\chi_-\rangle$; $\Psi_d = |\downarrow_z\rangle \otimes |\chi_+\rangle$. Remember that the tensor product of the bases in two spaces is a basis in the tensor product space]. ¶
Show that M is Hermitian.¶
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The basic idea behind the Spontaneous Localization approach is that TDSE is not quite right and has to be modified to solve the measurement problem. Since the linearity of TDSE causes troubles, in effect the modification consists in the addition of some non-linear terms in order to eliminate the superposition of macroscopically distinct states and to guarantee the definiteness of individual experimental outcomes. The difficulty consists in having the modified TDSE behave as the original TDSE as far as microscopic systems are concerned, but behave in the appropriately differently in the macroscopic case. Different proposals have been put forth; however, they share the view that ordinary position space, as compared to other configuration spaces, is privileged, and that the distinct states of the macroscopic apparatus, such as the possible pointer positions, must be macroscopically separate.

Without getting into any details, we shall consider, in semi-qualitative terms, just the theory (GRW) put forth by Ghirardi, Rimini, and Weber by way of an example (Ghirardi, G. C., Rimini, A., and Weber, T., (1986)). Consider a spin-half particle in state $|\uparrow\rangle$ going through a SGX device, and suppose we want to know whether $S_x = \hbar/2$ or

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[3] The Copenhagen interpretation, as put forth by Bohr and Heisenberg, bypasses the measurement problem by forbidding the quantum–mechanical description of the measuring device in the measurement set-up. Note, then that it significantly differs from von Neumann's. The role of consciousness in quantum measurement has been emphasized by Wigner and others, as we shall see later.

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$S_x = -\hbar/2$. One way to find out is to correlate the particle's x-spin component with a pointer's position. Things are set up in such a way that $S_x = \hbar/2$ is correlated with the pointer being in state $|\psi +\rangle$ at position +1 and $S_x = -\hbar/2$ with the pointer being in state $|\psi -\rangle$ at position −1. The wave function of the composite system, then is

$$|\Psi\rangle = \frac{1}{\sqrt{2}}|\uparrow_x\rangle \otimes |\psi_1^+\rangle \otimes, ..., \otimes|\psi_N^+\rangle + \frac{1}{\sqrt{2}}|\downarrow_x\rangle \otimes |\psi_1^-\rangle \otimes, ..., \otimes|\psi_N^-\rangle, \qquad (10.2.1)$$

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where the various $|\psi\rangle$'s are the eigenfunctions associated with specific particle positions and *N* is the number of particles in the pointer.

GRW requires that a wave function be subject not only to TDSE but also to spontaneous localization processes in ordinary space (whence the centrality of position) in which the spread *d* of, say, the wave function $|\psi_i^+\rangle$ is reduced almost to nothing.[4] Then, the first addendum in (10.2.1) *de facto* disappears and we are left with the pointer telling us that $S_x = -\hbar/2$. These localizations, which although not due to measurement are essentially quasi-collapses, occur randomly; however, the rate at which they take place depends on two quantities, a constant $\tau \cong 10^{15} s$ and *N*. In fact, the average time between localizations is given by τ / N. Consequently, in a microscopic system, the average time between spontaneous collapses is very large and therefore the behavior of

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[4] But not to nothing, otherwise we would have a true orthodox collapse and the uncertainty in momentum would become infinite. In effect, the localization function, instead of being a Dirac delta function, with *d* an infinitesimal length, is bell-shaped: narrow enough ($d \approx 10^{-7} m$) to produce, as far as experiment goes, effects indistinguishable from a true collapse, and wide enough to avoid too much momentum uncertainty.

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Although GRW is clear and completely physicalistic (there is no appeal to conscious observers as von Neumann's theory), it has some problems. As spontaneous localization theory cooks up TDSE to obtain the desired outcomes mimicking standard collapse, one's first impression is that such theory is *ad hoc*. However, perhaps such criticism is somewhat unjustified, since such a procedure is rather common. For example, Newton obtained the law of universal gravitation by cooking it up so that together with his laws of mechanics he would be able to obtain Kepler's laws about planetary motions. The GRW procedure is similar. Of course, with law of universal gravitation eventually one could also calculate the paths of comets, about which Kepler's laws are silent. Similarly, SL theories provide both a border between the microscopic and the macroscopic world and a physical mechanism for the emergence of a definite

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[5] New varieties of SL have been advanced which have been made relativistic and which substitute the random localizations with continuous localization. For a mathematical analysis of the various SL theories, see Home, D., (1997): 97-116, and Omnès, R., (1999): 248-56.

return in a single experiment. As such, they are both explanatory and (in principle) experimentally falsifiable.

However, there are more serious difficulties. Part of the outcome of the quasi-collapses is to eliminate interference, the very thing that we know decoherence, a process we shall consider in the next chapter, does for all practical purposes. But, Omnès has argued, decoherence time is much shorter than that required by spontaneous localization, and consequently a principle of economy intimates that at least at this stage of the measurement process spontaneous localization is unneeded (Omnès, R., (1999): 250-55). Still, decoherence can at most produce improper mixtures, perhaps one could say that decoherence triggers the much slower spontaneous localization that produces the proper mixture required for measurement outcomes.[6]

10.3 Everett's Universal Wave Function Approach

One of the ways to avoid the measurement problem is to deny the observer's reliability principle and hold that when it seems to us that the pointer is at a certain position and nowhere else we are in fact, at least to some extent, deluded. There are several versions of this approach, but all of them can be traced back to Everett's views, and therefore it is to these that we now briefly turn.

Typically, quantum mechanics predicts that various alternatives, with associated probabilities, are possible. Everett developed the idea that allowing the simultaneous existence of all these alternatives can be used to render quantum mechanics with EE and

[6] For a more technical (but still readable) criticism questioning whether SL theories can really account for all types of measurement, see Albert, D. Z., and Vaidman, L., (1988); Albert, D. Z., (1992): 92-111.

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A further difficulty is that it is far from clear whether SL theories can really account for all types of measurement. Albert and Vaidman have come up with the following scenario. (Albert, D. Z., and Vaidman, L., (1988); Albert, D. Z., (1992): 92-111). Consider the SGX example described above with one crucial difference: instead of pointers, we have two locations A and B on a fluorescent screen lighting up when one of the particles coming out of the SGX device hits it. Let us now follow the particle and see whether GRW delivers an experimental outcome, that is, the appropriate correlation between the value of S_x and the lighting up at A or B. Let us proceed step by step. ¶
First step: the particle is in flight between SGX and the screen. Since N=1, the system's evolution is effectively described by TDSE, and therefore GRW's mechanism for mimicking collapse does not kick in yet, as it were. ¶
Second step: the particle hits the screen and it kicks some of the electrons of the fluorescent atoms into excited orbitals. Then, the state of the system is given by the superposition¶

$$|\Psi\rangle = \frac{1}{\sqrt{2}}|\uparrow_x\rangle \otimes |A\rangle \otimes |e_1^+\rangle \otimes,$$

$$+\frac{1}{\sqrt{2}}|\downarrow_x\rangle \otimes |B\rangle \otimes |e_1^-\rangle \otimes, ..., \otimes$$

(18.2.2)¶
where $|A\rangle$ indicates that the particle is at A, $|e_1\rangle,...|e_i\rangle$ are the states of the fluorescent electrons near A, $|B\rangle$ indicates that the particle is at B, $|e_{i+1}\rangle,...,|e_N\rangle$ are the states of the fluorescent electrons near B, $|e^+\rangle$ indicates that the electron is excited, and finally $|e^-\rangle$ indicates that the electron is at ground state. Suppose now that the wave function of electron e_i undergoes localization, that is, suppose that its spread is $d \approx 10^{-7} m$. Will this be sufficient to make one of the two addenda in (18.2.2) *de facto* equal to zero? Since the states of the electrons are distinguished not in terms of position, but in terms of energy levels, the quest ... [1]

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without collapse compatible with experience.[7] In effect, he tried to eliminate the collapse postulate from quantum mechanics and explain the empirical predictions of the theory as *subjective* representations of observers who are treated as ordinary physical systems. The result, Everett claimed, is a "novel situation in which the formal theory is objectively continuous and causal while subjectively discontinuous and probabilistic" (Everett, H., (1973): 9).

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The basic idea is to consider quantum mechanics as providing the physics for every isolated system, whether it includes an observer or not. As we know, this runs immediately into the measurement problem, symbolized by

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$$|\Psi'\rangle = \sum_i c_i |\psi_i\rangle \otimes |\chi_i\rangle. \qquad (10.3.1)$$

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Everett thought that one could avoid the problem by appealing to the notion of *relative state*. He conceded that after measurement only the total system S+D is in a definite

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[7] The antecedent of this idea can be found in Schrödinger: "The idea that they be not alternatives but *all* really happen simultaneously seems lunatic [to the quantum theorist], just *impossible*. He thinks that if the laws of nature took *this* form, let me say, a quarter of an hour, we should find our surroundings rapidly turning into a quagmire, or sort of featureless jelly or plasma…It is strange that he should believe this. For I understand he grants that unobserved nature does behave this way—namely according to the wave equation (Quoted in Barrett, J., A., (1999): 63). Schrödinger thought that TDSE is all one needs if one is ready to abandon the preconceptions that we observe particles and not waves. Alas, the idea does not really work because typically wave packets spread. In the remainder of this chapter, we often follow Barrett's discussion.

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quantum state, and consequently there is no absolute matter of fact about D's states. However, Everett noted, it is possible to attribute to D the state $|\chi_i\rangle$ relative to state $|\psi_i\rangle$ of S, state $|\chi_2\rangle$ relative to state $|\psi_2\rangle$ of S, and so on. So, while the observer D is one individual physical system throughout the measurement process, its state splits into different simultaneously existing branches, each representing "a different outcome of the measurement and the *corresponding* eigenstate of the object-system state" (Everett, H., (1957) in De Witt, B., and Graham, N., (eds.) (1973): 146).

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Of course, D has no inkling of the fact that what he experiences is just a relative matter of fact, but Everett thought that this problem could be overcome. For, he claimed, arguments to the effect

> that the world picture presented by this theory is contradicted by experience, because we are unaware of any branching process, are like the criticism of the Copernican theory that the mobility of the Earth is a real physical fact is incompatible with the common sense interpretation of nature because we feel no such motion. In both cases, that argument fails when it is shown that the theory itself predicts that our experience will be what it is in fact (Ibidem, 146-47).

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However, Everett was not forthcoming with the theoretical explanation for the belief that we do not experience relative matters of fact. In fact, his explanations, such as they are, are relegated in two footnotes in the two papers in which he presented his position. As far as one can make out, he seems to have thought that our inability to be aware of the splitting process (namely, be aware of the other relative states) is due to "the lack of effect of one branch on another" (Ibidem, 147). What he had in mind when he used the

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word “effect” is far from clear. Obviously, it would seem that physical influence among branches is impossible; however, the branches are connected because the final system S+D is a pure state rather than a mixed state and therefore it allows interference effects among the state components. Ultimately, because of its lack of detail Everett’s interpretation falls short, or, more charitably, stands in need of clarification and development.[8] In effect, two main ways of developing Everett’s idea have emerged: one interprets the different branches of the universal wave function as literally referring to different worlds; the other associates the branches to correspond with a mind having certain beliefs. Both accept EE.

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10.4 The Many-Worlds Interpretation

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DeWitt thought that the best way of understanding Everett’s ideas is by assuming that every element of the superposition (10.3.1) describes a real world.[9] In other words, while the universal function describes the global state of the universe, each element of the superposition describes a local state, a world. So, (10.3.1) describes *i* worlds, all existing simultaneously, in each of which D registers a determinate measurement return. Of course, the nature of the elements of the superposition depends on the choice of basis, and therefore there are bases in which D does not obtain determinate measurement

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[8] For an extensive analysis, see Barrett, J., A., (1999): ch. 3.

[9] DeWitt, B., (1971). Whether this corresponds to Everett’s views, is unclear. On the one hand, Everett explicitly claimed that the observer is one physical system throughout the measuring process, which would seem to rule out the many worlds interpretation. On the other hand, however, he did not criticize the many worlds interpretation as a misrepresentation of his own views.

returns. In other words, $|\Psi'\rangle$ in (10.3.1) could be expanded in an infinity of different ways, depending on the choice of basis (observable). However, one can impose the restriction that the expansion basis be such that D does have a determinate reading in each world. In other words, although mathematically all bases are the same, one may assume that physically they are not: there are preferred bases in which the pointers of measurement devices do point, and observers do record that. In sum, the evolutionary law of the universe is given by TDSE, there is no collapse, and the experience of determinate results is explained by the splitting of the universe into a myriad of worlds, one for each measurement or "quantum transition." To obtain a kind of visual representation of the many-worlds interpretation, we can use figure 2 in chapter 8, where the branches of the tree represent each a world as it goes through time.

The many worlds interpretation has been criticized on several grounds. To many, the exuberant ontology it entails seems unduly extravagant and seriously guilty of multiplying entities without necessity. However, one might retort that the multiplication of worlds buys fundamental ontological simplification in that the collapse rule is eliminated. Simplicity, one might argue, is to be sought in fundamental principles, not in the number of derivative items a theory holds to exist. In fact, one might even welcome the ontological bounty the theory envisages on the theological ground that being is good. Still, it is incumbent on DeWitt to explain when the multiplication of worlds occurs. DeWitt claims that it occurs when "measurement-like interactions" and "quantum transitions" take place. However, he does not tell us what counts as a measurement-like interaction or a quantum transition, although from the claim that the latter takes place "on every star" one can reasonably infer that it does not involve observation (DeWitt, B.,

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If we focus on successive spin-half measurements on the particles of an ensemble, at each measurement the world splits into two copies, one in which the return is +1 and one in which it is –1. The

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(1970) in De Witt, B., and Graham, N., (eds.) (1973): 161). Presumably, an interaction between a quantum system and a macroscopic system would count as a quantum transition, but it is not clear what one ought to say about microscopic interactions; for example, how strong must the interaction be in order to have a splitting of the universe?

Another objection, emphasized by both Albert and Barrett, is that the many-worlds theory is unable to account for the probabilistic aspect of quantum mechanics. At first blush, given that every summand in (10.3.1) describes a world it would seem natural to say that world $|\psi_i\rangle \otimes |\chi_i\rangle$ obtains with probability $|c_i|^2$. However, this cannot be right because according to the many worlds interpretation *all* worlds exist simultaneously. Perhaps, one could claim that there is a probability $|c_i|^2$ that the experimenter ends up in the world described by $|\psi_i\rangle \otimes |\chi_i\rangle$, that is, there is a probability $|c_i|^2$ that *one's* world develops into the world described by $|\psi_i\rangle \otimes |\chi_i\rangle$. But it is hard to make much sense of this suggestion. One's immediate future, as it were, involves many slightly different worlds each containing a slightly different copy of one. It looks as if one actually ends up in many worlds, if that makes any sense. The problem here is that talking sensibly about personal identity through time with selves constantly splitting into almost identical copies of the original and inhabiting physically disconnected worlds is a tall order to put it mildly. Worse, without some account of the identity of physical items through time, one can hardly talk about repeated measurements on the same system or, more generally, empirical predictions of results obtained at different times. Consequently, the many worlds interpretation must engage in substantive and very controversial metaphysics in order to succeed.

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Even granting the metaphysics, since all physically possible worlds within the framework of preferred bases exist simultaneously, there are world-branches in which the usual statistical results of quantum mechanics do not apply. So, why are we not in such a world? The suggestion that such branches are simply absent is in conflict with the basic idea behind the many worlds interpretation that all the terms in (10.3.1) are on the same footing. Alternatively, one may invoke the anthropic principle that although such worlds do exist, they are nevertheless without intelligent life capable of recording such statistics (DeWitt, B., (1970) in De Witt, B., and Graham, N., (eds.) (1973): 163). That is, we humans can exist only in a branch in which the usual statistical results of quantum physics obtain. But of course, since we have little sense of what quantum arrangements are necessary to support of intelligent life, there might be other branches in which other intelligent beings obtain different statistical returns.

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Another objection has to with the lack of awareness of the splitting process. If my world splits into many almost identical copies every time a measurement or a quantum transition occurs, the splitting must occur at a phenomenal rate. So, why are we unable to detect it? The answer, DeWitt claims, is that no experiment can detect the presence of the other worlds (Ibidem, p. 165). But the only way to insure such a result is to assume that the different worlds lie on space-time structures that are disconnected, so that no physical relation can exist among them. So, an apparently trivial event like my measuring the spin of an electron causes a global split of space-time, and this seems simply preposterous (Earman, J., (1986): 224).

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10.5 The One and the Many Minds Interpretation

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18.

Broadly speaking, while the many worlds interpretation takes each branch in Everett's tree to describe a world, the many minds interpretation takes each branch to correspond to a mind having certain beliefs. There are different and incompatible versions of this interpretation, but most of them share a common story about mental dynamics that is based on three rules.

The first rule (R1) says that each term in (10.3.1) corresponds to a mind having the appropriate belief. So, for example, suppose that after measurement the system is in state

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$$|\Psi\rangle = \left(\frac{1}{2}|\uparrow_z\rangle \otimes |\chi_+^w\rangle + \frac{\sqrt{3}}{2}|\downarrow_z\rangle \otimes |\chi_-^w\rangle\right), \qquad (10.5.1)$$

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where $|\chi_+^w\rangle$ represents the brain of observer W being in the physiologically appropriate state resulting from its interaction with an SGZ recording +1, and $|\chi_-^w\rangle$ represents the brain of observer W being in the physiologically appropriate state resulting from its interaction with an SGZ recording -1. Then, $|\uparrow_z\rangle \otimes |\chi_+^w\rangle$ corresponds to a mind associated with observer W believing that the measurement return is +1, and $|\downarrow_z\rangle \otimes |\chi_-^w\rangle$ corresponds to a mind associated with observer W believing that the measurement return is –1.

The second rule (R2) says that the probability of having certain beliefs is equal to the squared modulus of the expansion coefficient of the associated quantum term in the vector expansion. Hence, in the example the probability of W believing that he has gotten the measurement return –1 is 3/4.

The third rule (R3) says that R2 applies only to those terms in the expansion of $|\Psi\rangle$ that are compatible with the previous part of the branch representing W's mind. In other words, R3 tells us to eliminate those terms that are incompatible with W's past beliefs about measurement returns and then renormalize the state vector.[10] The rationale for R3 can be seen as follows. Suppose that once (10.5.1) obtains, W believes he got +1 as a measurement return. Imagine now that W decides to re-measure S_z. Then, if everything works properly, the state vector will become

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$$|\Psi'\rangle = \left(\frac{1}{2}|\uparrow_z\rangle \otimes |\chi_+^w, \chi_+^w\rangle + \frac{\sqrt{3}}{2}|\downarrow_z\rangle \otimes |\chi_-^w, \chi_-^w\rangle\right), \qquad (10.5.2)$$

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where $|\chi_+^w, \chi_+^w\rangle$ symbolizes getting +1 twice. An indiscriminate application of R2 would lead to the conclusion that, corresponding to $|\uparrow_z\rangle \otimes |\chi_+^w, \chi_+^w\rangle$, there is a 25% probability that W will believe he got +1 twice , and that, corresponding to $|\downarrow_z\rangle \otimes |\chi_-^w, \chi_-^w\rangle$, there is a 75% probability that W will believe he got –1 twice. But then W will be wrong 75% of the times, since in the first measurement he got +1. R3 tells us to eliminate $|\downarrow_z\rangle \otimes |\chi_-^w, \chi_-^w\rangle$ and renormalize the state vector, so that R2 will tell us that there is a 100% probability that W will believe he got +1 twice. This is the outcome one would want to have in order to guarantee that O is right at least about his own past beliefs if not about the physical state of the world.

Of course, since the actual physiological state of W's brain is a superposition one has to assume that the minds involved are not physical entities, since the associated

[10] Of course, the elimination of expansion terms and the renormalization apply only within the mental dynamics and not within the physical dynamics.

observers do have definite beliefs. In fact, the dualism entailed by the many minds interpretations must involve more than epiphenomenalism, for it is hard to see how different minds could emerge out of the same superimposed state, given that pure states are not mixed states.[11] However, in contrast with interactionism, according to which the mind (an immaterial substance) interacts with the body, one may assume that the physical world is causally closed in the sense that no immaterial mind causes anything in it, thus avoiding potential conflicts with conservation laws. It is also worth nothing that although W believes that he got +1 (or -1, as the case may be) as a measurement return, EE tells us that in reality he got neither, since the SGZ is also in a state of superposition. Hence, although the theory aims at explaining why we believe we got certain measurement returns, it also entails that we are systematically wrong in our beliefs about the physical world.

One way to develop the many minds interpretation is to assume that at any time one and only one branch represents an actual mind, while all the other branches represent only possible but unactualized minds. Let us call this the "single mind interpretation" (Albert, D. Z., (1992): 126-29). Then, an observer's brain (which, remember, is in a state of superposition) will be associated with one and only one mind. Then, because of (R3) one's present beliefs will be in accordance with one's past beliefs, and because of (R1) and (R2) they will also be in accordance with quantum mechanical statistics.

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However, the single mind interpretation suffers from two major problems. First, nothing in the state vector determines which mind is actual and which is not. In effect,

[11] Epiphenomenalism is the view that mental states are effects of brain activity but are causally inert, just surface phenomena with no causal power.

then, one must introduce the mental equivalent of the collapse postulate in order to bring one and only one mind out of potentiality. But then perhaps one might as well stick with the orthodox interpretation. It is true that collapse applied only to minds is perhaps less ontologically demanding than collapse applied to physical systems as well, but at least in the orthodox interpretation collapse is supposed, albeit obscurely, to be brought about by measurement, while in the single mind interpretation it just appears out of the blue.

Second, the single mind interpretation fails to coordinate the beliefs of actual individual minds, and therefore it leads to solipsism. To see why, consider the state

$$|\Phi\rangle = \left(\frac{1}{2}|\uparrow_z\rangle \otimes |\chi_+^w\rangle \otimes |\chi_+^p\rangle + \frac{\sqrt{3}}{2}|\downarrow_z\rangle \otimes |\chi_-^w\rangle \otimes |\chi_-^p\rangle\right), \qquad (10.5.3)$$

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where the first term corresponds to observers W and P believing that they got +1 as a measurement return, and the second term corresponds to W and P believing that they got –1. Since $|\Phi\rangle$ does not determine which minds are actual, it may happen that W's mind is associated with the first term and P's mind with the second. Hence, W will think that both W and P believe they have obtained +1 and P will think that both W and P believe they have obtained –1. Hence, W and P will have incompatible beliefs. Clearly, the problem is the lack of coordination among the beliefs of the two observers. Of course, one could modify R3 to obtain such coordination by demanding that all minds be associated with the same branch. So, in our example, both W and P would have to be associated either with the first or the second term in the state vector expansion (Barrett, J., A., (1999): 191). The result would be the creation of a sort of preestablished harmony among minds, which seems preposterous.

Another attempt at solving the coordination problem consists in allowing all the minds associated with any branch to exist simultaneously. Let us call this the "many

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minds interpretation" (Albert, D. Z., (1992): 130-33). An observer's brain, then, will be associated with more than one mind, in fact with a continuous infinity of minds. In addition, the percentage of such minds having a certain belief will be equal to the squared modulus of the expansion coefficient of the term in MP associated with that belief by (R1)-(R3). So, in the above example, W will be associated with an infinity of minds, 25% of which (let us call any of them "W_+") believe that both W and P got +1, and 75% of which (let us call any of them "W_-") believe that they both got –1. A completely analogous story, involving P_+ and P_- will apply to P. But then any of W_+'s beliefs about this specific measurement will be coordinated with any of P_+'s, and any of W_-'s with any of P_-'s. Hence, the coordination problem is solved: if W and P witnessed the result of the very same experiment, then a W_+ will be talking, as it were, to a P_+, and a W_- to a P_-. That is, there will be minds that agree about what measurement results they have obtained although, of course, no measurement results have been obtained since STDE is the correct description of the physical story and there is no collapse.

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In addition, Albert has argued that the many minds interpretation is local (Albert, D. Z., (1992): 131-32). In fact, consider the EPR situation expressed by

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$$\frac{1}{\sqrt{2}}\left(|\uparrow_z^a\downarrow_z^b\rangle\otimes|\chi_+^a\rangle_W\otimes|\chi_-^b\rangle_P-|\downarrow_z^a\uparrow_z^b\rangle\otimes|\chi_-^a\rangle_W\otimes|\chi_+^b\rangle_P\right), \qquad (10.5.4)$$

where observer W is at *a*'s location and observer P at *b*'s. When W performs his measurement on *a*, rules R1-R3 entail the following. Half of W's minds will believe that he got +1 and P got –1, and the other half that he got –1 and P got +1. A completely analogous story is true of P upon his measurement on *b*. Hence, when W and P compare their results, the appropriately correlated minds will "talk" to each other. Since there is no collapse, no transition from potentiality to actuality (all the minds are actual), the issue

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of non-locality does not arise. However, the price the many minds interpretation pays is high. Every observer is associated with an infinity of non-communicating minds holding incompatible beliefs, and the thought of many deluded minds simultaneously "using" the same body to communicate different measurement returns to other minds seems crazy.

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Exercises

Exercise 10.1

1. Verify (10.1.8). [Hint. Set $\Psi_a = |\uparrow_z\rangle \otimes |\chi_+\rangle$; $\Psi_b = |\downarrow_z\rangle \otimes |\chi_-\rangle$; $\Psi_c = |\uparrow_z\rangle \otimes |\chi_-\rangle$; $\Psi_d = |\downarrow_z\rangle \otimes |\chi_+\rangle$. Remember that the tensor product of the bases in two spaces is a basis in the tensor product space].

2. Show that M in (10.1.7) is Hermitian.

Answers to the Exercises

Exercise 10.1

1.

$(|\Psi_a\rangle\langle\Psi_a| + |\Psi_b\rangle\langle\Psi_b|)|\Psi_a\rangle = |\Psi_a\rangle\langle\Psi_a|\Psi_a\rangle + |\Psi_b\rangle\langle\Psi_b|\Psi_a\rangle = |\Psi_a\rangle$ because $|\Psi_a\rangle$ and $|\Psi_b\rangle$ are orthonormal. In addition, $(|\Psi_a\rangle\langle\Psi_a| + |\Psi_b\rangle\langle\Psi_b|)|\Psi_c\rangle = |\Psi_a\rangle\langle\Psi_a|\Psi_c\rangle + |\Psi_b\rangle\langle\Psi_b|\Psi_c\rangle = 0$ because $|\Psi_c\rangle$ is orthonormal to $|\Psi_a\rangle$ and $|\Psi_b\rangle$. The other two cases are proved analogously.

2. $$[(|\uparrow_z\rangle \otimes |\chi_+\rangle)(\langle\chi_+| \otimes \langle\uparrow_z|) + (|\downarrow_z\rangle \otimes |\chi_-\rangle)(\langle\chi_-| \otimes \langle\downarrow_z|)]^+ =$$
$$(|\uparrow_z\rangle \otimes |\chi_+\rangle)(\langle\chi_+| \otimes \langle\uparrow_z|) + (|\downarrow_z\rangle \otimes |\chi_-\rangle)(\langle\chi_-| \otimes \langle\downarrow_z|)$$

that is, $M^+ = M$.

Deleted: **Summary**¶
Solutions to the measurement problem that deny the universal validity of TDSE.¶
<#>von Neumann: A measurement involves a chain at one end of which is the quantity being measured and at the other end is the observing subject.¶
TDSE does not give a correct account of the whole measurement process. After entanglement, the state vector collapses onto one of the eigenvectors of the operator representing the measured dynamical observable. (Projection Postulate). It does not matter when in the measuring process the collapse takes place because at the end the measurement returns are the same. ¶
Problems:¶
<#>If collapse is a physical event, the time of its occurrence is empirically relevant. ¶
<#>At measurement, all that happens is an energy exchange within the closed system made up of the observed system and the apparatus, and TDSE should deal with that. ¶
<#>Rovelli's operator: $M = (|\uparrow_z\rangle \otimes |\chi_+\rangle)(\langle\chi_+| \otimes \langle\uparrow_z|$
. It determines when the correlation between observable and measurement apparatus occurs, suggesting that already then the pointer of the apparatus is at some definite position. However, *M* itself is subject to all the usual interpretive ambiguities. ¶
<#>GRW (a type of spontaneous localization theory): Non-linear terms are added to TDSE so that the wave function undergoes random spontaneous localization processes in such a way as to minimize collapse at the micro-level but obtain the correct expectation values at the macro-level.¶
Problems:¶
<#>The theory seems ad hoc. ¶
<#>In some respects it duplicates the effects of decoherence, which is much faster. ¶
<#>It is at best doubtful that it can account for all types of measurement. ¶
¶
Solutions to the measurement problem that deny the observer's reliability principle. ¶
<#>Everett: Although the observer is one individual physical system throughout the measurement process, by appealing to the notion of relative state one can hold that its state splits into different simultaneously existing branches, each representing a different outcome of the measurement. The observer is unaware of the splitting. ¶
Problem: It is hard to tell what the theory really amounts to.¶
<#>Many worlds interpretation (DeWitt): while the universal vector in a stat ... [2]

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A further difficulty is that it is far from clear whether SL theories can really account for all types of measurement. Albert and Vaidman have come up with the following scenario. (Albert, D. Z., and Vaidman, L., (1988); Albert, D. Z., (1992): 92-111). Consider the SGX example described above with one crucial difference: instead of pointers, we have two locations A and B on a fluorescent screen lighting up when one of the particles coming out of the SGX device hits it. Let us now follow the particle and see whether GRW delivers an experimental outcome, that is, the appropriate correlation between the value of S_x and the lighting up at A or B. Let us proceed step by step.

First step: the particle is in flight between SGX and the screen. Since N=1, the system's evolution is effectively described by TDSE, and therefore GRW's mechanism for mimicking collapse does not kick in yet, as it were.

Second step: the particle hits the screen and it kicks some of the electrons of the fluorescent atoms into excited orbitals. Then, the state of the system is given by the superposition

$$\left|\Psi\right\rangle = \frac{1}{\sqrt{2}}\left|\uparrow_x\right\rangle \otimes \left|A\right\rangle \otimes \left|e_1^+\right\rangle \otimes,\ldots,\otimes\left|e_i^+\right\rangle \otimes \left|e_{i+1}^-\right\rangle \otimes,\ldots,\otimes\left|e_N^-\right\rangle + \\ + \frac{1}{\sqrt{2}}\left|\downarrow_x\right\rangle \otimes \left|B\right\rangle \otimes \left|e_1^-\right\rangle \otimes,\ldots,\otimes\left|e_i^-\right\rangle \otimes \left|e_{i+1}^+\right\rangle \otimes,\ldots,\otimes\left|e_N^+\right\rangle$$

(18.2.2)

where $\left|A\right\rangle$ indicates that the particle is at A, $\left|e_1\right\rangle,\ldots\left|e_i\right\rangle$ are the states of the fluorescent electrons near A, $\left|B\right\rangle$ indicates that the particle is at B, $\left|e_{i+1}\right\rangle,\ldots,\left|e_N\right\rangle$ are the states of the fluorescent electrons near B, $\left|e^+\right\rangle$ indicates that the electron is excited, and finally $\left|e^-\right\rangle$ indicates that the electron is at ground state. Suppose now that the wave function of electron e_i undergoes localization, that is, suppose that its spread is $d \approx 10^{-7} m$. Will this be sufficient to make one of the two addenda in (18.2.2) *de facto* equal to zero? Since the states of the electrons are distinguished not in terms of position, but in terms of energy levels, the question is whether *d* can distinguish $\left|e_i^+\right\rangle$ and $\left|e_i^-\right\rangle$ in terms of position. The answer is negative, since the distance between a stationary and an excited orbital is much smaller than *d*. So, at this stage GRW does not produce the definite outcome we want.

Third step: since excited orbitals are unstable, in a very short time, the electrons revert to the ground states emitting photons in the process. Here, (18.2.2) would finally develop into a state vector in which the photons emitted at A and those emitted at B have a difference in position (a few centimeters) that is much larger than *d*. However, in a time much too short for GRW to operate, the wave packets of the various photons will overlap in position space, and even at this stage GRW will fail to mimic standard collapse.

We can summarize the situation by saying that *d* is too large for orbitals and τ too long for photons. So, the modified TDSE that was cooked up to produce the desired pointers results is unable to deliver the same results when fluorescent screens are used. Hence, the analogy between GRW and the law of universal gravitation breaks down, and the constants of GRW do seem too much *ad hoc*. Of course, one could add further steps, taking into account the retina or the brain states of the experimenter, but then GRW leaves physics to get into the idiosyncrasies of human physiology.

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Summary

Solutions to the measurement problem that deny the universal validity of TDSE.

von Neumann: A measurement involves a chain at one end of which is the quantity being measured and at the other end is the observing subject.

TDSE does not give a correct account of the whole measurement process. After entanglement, the state vector collapses onto one of the eigenvectors of the operator representing the measured dynamical observable. (Projection Postulate). It does not matter when in the measuring process the collapse takes place because at the end the measurement returns are the same.

Problems:

If collapse is a physical event, the time of its occurrence is empirically relevant.

At measurement, all that happens is an energy exchange within the closed system made up of the observed system and the apparatus, and TDSE should deal with that.

Rovelli's operator: $M = \left(|\uparrow_z\rangle \otimes |\chi_+\rangle\right)\left(\langle\chi_+| \otimes \langle\uparrow_z|\right) + \left(|\downarrow_z\rangle \otimes |\chi_-\rangle\right)\left(\langle\chi_-| \otimes \langle\downarrow_z|\right)$. It determines when the correlation between observable and measurement apparatus occurs, suggesting that already then the pointer of the apparatus is at some definite position. However, M itself is subject to all the usual interpretive ambiguities.

GRW (a type of spontaneous localization theory): Non-linear terms are added to TDSE so that the wave function undergoes random spontaneous localization processes in such a way as to minimize collapse at the micro-level but obtain the correct expectation values at the macro-level.

Problems:

The theory seems ad hoc.

In some respects it duplicates the effects of decoherence, which is much faster.

It is at best doubtful that it can account for all types of measurement.

Solutions to the measurement problem that deny the observer's reliability principle.

Everett: Although the observer is one individual physical system throughout the measurement process, by appealing to the notion of relative state one can hold that its state splits into different simultaneously existing branches, each representing a different outcome of the measurement. The observer is unaware of the splitting.

Problem: It is hard to tell what the theory really amounts to.

Many worlds interpretation (DeWitt): while the universal vector in a state of superposition describes the global state of the universe, at every measurement or quantum transition each element of the superposition describes a world within which a determinate outcome takes place.

Problems:

There is an exuberant ontology, with each world constantly splitting into new ones.

It is difficult to account for the probabilistic aspect of quantum mechanics and for the lack of awareness of the splitting process.

One needs to appeal to the anthropic principle to rule out worlds falsifying the quantum mechanics.

Quantum mechanics but not conservation of energy applies at the level of the universe as a whole.

The single mind interpretation: Each term in the measurement superposition corresponds to a mind having the appropriate belief (R1). The probability of having certain beliefs is equal to the squared modulus of the expansion coefficient of the associated quantum term in the vector expansion (R2). R2 applies only to those terms in the measurement superposition that are compatible with the previous part of the branch representing the observer's mind (R3). Only one of the minds actually exists; the others are only potential. The minds are not physical entities, although interactionism is not entailed.

Problems:

The state vector does not determine which mind is actual and which is not, and consequently the mental equivalent of the collapse postulate must be introduced.

The beliefs of actual individual minds are not coordinated.

The many minds interpretation: acceptance of (R1)-(R3). However, an observer's brain is associated with an infinity of minds. The percentage of such minds having a certain belief will be equal to the squared modulus of the expansion coefficient of the term in the measurement superposition associated with that belief by (R1)-(R3). This solves the coordination problem. In addition, this interpretation is local.

Problem: The idea that every observer is associated with an infinity of non-communicating minds holding incompatible beliefs, and the thought of many minds simultaneously using the same body to communicate different measurement returns to other minds seems preposterous.

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