

The Many-Worlds Interpretation of Quantum Mechanics Is Fatally Flawed

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Abstract

The linear mathematics of quantum mechanics gives many versions of reality instead of the single version we perceive, with the perceived version chosen at random according to a probability law. Because of these peculiarities, the theory requires an interpretation to be fully understood. Over 50 years ago, Everett proposed in his many-worlds interpretation that these characteristics could be accounted for if the mathematics itself, with no collapse or hidden variables, was carefully analyzed. We show this is incorrect; the linear mathematics cannot account for the probability law. Thus the many-worlds interpretation is not viable. Some mechanism, such as collapse or hidden variables, must be added to obtain a satisfactory understanding of the physical universe.

1. Introduction

Quantum mechanics, which consists of a set of linear equations for the state vector, gives an accurate description of a wide range of phenomena. But this theory has one most peculiar property; the state vector, which is essentially equivalent to the more familiar wave function, often contains several simultaneously existing versions of reality. In the Schrödinger's cat experiment, for example, the cat is both alive and dead at the same time. Experientially, we perceive only one version—cat alive or cat dead—but quantum mechanics does not indicate which one. Instead, it gives the *probability* of perceiving a particular version.

Thus the mathematics of quantum mechanics seems to leave us with two unanswered questions: Why do we perceive just one version of reality when there are often several in the state vector? And why, if an experiment is repeated many times, are the frequencies of the versions we perceive governed by a probability law? It is this second question which is of primary interest here.

Schemes which attempt to answer these questions are called interpretations of quantum mechanics. One major interpretation is to suppose there are actual particles (or "hidden" particle-like variables), that the particles ride along on and single out just one version of reality, and that it is the singled-out version which we perceive [1,2]. A second major interpretation is to suppose there is some process, outside the conventional laws of quantum mechanics, which collapses the wave function down to just one version [3-5]. If this process collapses the dead-cat version in the

Schrödinger's cat case for example, we would perceive a live cat. There is currently no convincing evidence for either of these interpretations [6].

A third possibility is Everett's [7] many-worlds interpretation (MWI) which claims that a careful examination shows both questions can be answered using only the mathematics of quantum mechanics itself. All that seems to be needed to fully understand the relation between the mathematics and our perceived reality is to give up the idea that there is a single, unique version of each of us. It is this interpretation, currently one of the major possible ways to understand quantum mechanics, which is examined here.

We find the MWI falls short because it cannot account for probability. First, every possible outcome is perceived on every run of an experiment so probability of perception cannot even be *defined* in the MWI. In addition, when an experiment is run many times, the probability law implies restrictions on the perceived outcomes; states with outcomes not near those predicted by the probability law are never perceived. But these restrictions flatly contradict the principles of the MWI, where every version is always perceived. Thus, because the MWI cannot account for probability, it does not provide us with an acceptable interpretation of quantum mechanics.

2. Definition of the many-worlds interpretation

The MWI as we define it is based on a "pure" version of quantum mechanics which we call QM-A. The following seven principles describe the content and consequences of the mathematics of this unamended, linear equation, Hilbert space quantum mechanics.

- (1) Existence consists solely of the state vectors which obey the usual linear quantum mechanical equations of motion.
- (2) There are no particles or hidden variables.
- (3) There is no collapse of the state vector, so all the different versions of reality (Schrödinger's cat both alive and dead) continue forever.
- (4) The linear equations of motion do not single out any version of reality as being "more real" than any other.
- (5) There are no sentient beings, outside the laws of quantum mechanics, which look in from outside physical reality and perceive just one version of reality.
- (6) An observer is not different in principle from a recorder, an electronic device which records the readings on detectors.
- (7) If a version of an observer perceives an outcome, it is able to report that outcome. (By "report" we mean communicate to versions of other observers on the same branch of the state vector.)

There are also three clarifying remarks. First, the mathematics implies there can be no interaction, no means of communication, between the different versions of reality in the state vector. Thus different versions of the observer are not aware of the other versions or what they perceive. Second, the perceptions of which "I" am currently aware correspond to those of a single version of the observer—but there are many versions of "I". And third, no assumption regarding probability is made in the

definition of QM-A (because probability does not directly occur in the linear equations of motion even though conservation of probability—once probability is *assumed*—is implied by the equations).

Everett claimed that QM-A alone implied all the properties—the perception of only one version of reality, the perception of eigenvalues of operators, agreement among observers, the perception of the exposure of only one film grain by a spread-out wave function, an explanation of the photoelectric effect and other specific phenomena, the probability law, and so on—that are needed to explain our perception of physical existence. (See reference [6] and [8] for a fuller explanation of how most of these properties follow from the mathematics of quantum mechanics). But we will show here that QM-A cannot account for the probability law.

3. No probability in QM-A

Before discussing the experimentally verified probability law, we need to define it. If we schematically write the quantum state of Schrödinger’s cat as

$$\begin{aligned} & a_1 |cat\ alive\rangle + a_2 |cat\ dead\rangle \\ & \langle cat\ alive | cat\ alive\rangle = \langle cat\ dead | cat\ dead\rangle = 1 \\ & |a_1|^2 + |a_2|^2 = 1 \end{aligned}$$

where a_1, a_2 are numerical coefficients, then the probability of seeing a live cat is $|a_1|^2$. More generally, if the state vector contains several versions of reality, $|\Psi\rangle = \sum a_i |version\ i\rangle$, then the probability law says that the probability of perceiving version i is $|a_i|^2$.

To illustrate the problem with probability in QM-A, we do a Stern-Gerlach (S-G) experiment on a spin $\frac{1}{2}$ system, with $+1/2$ and $-1/2$ spin states. This is done in steps.

1. Single particle. After the particle-like state vector for, say, a spin $\frac{1}{2}$ silver atom, passes through the magnet, the state of the system is

$$\begin{aligned} |\Psi_1\rangle &= a_+ |\psi_+\rangle + a_- |\psi_-\rangle, \\ |a_+|^2 + |a_-|^2 &= 1 \end{aligned} \tag{1}$$

where the wave functions for the two states $|\psi_+\rangle$ and $|\psi_-\rangle$ travel on two different “trajectories.” It seems obvious that in QM-A there is no hint of probability of the *existence* of *either* version $|\psi_+\rangle$ or version $|\psi_-\rangle$ of the ‘particle’ in this system because both versions simultaneously exist. (They coexist in different regions of an abstract mathematical Hilbert space rather than existing together in our usual three-dimensional position space.)

2. Particle and two detectors. We now add detectors $|D+\rangle$ on the + trajectory and $|D-\rangle$ on the – trajectory. Then the equations of motion dictate that the resulting entangled state is (with Y standing for yes, detection, and N for no detection)

$$|\Psi_2\rangle = a_+ |\psi_+\rangle |D+,Y\rangle |D-,N\rangle + a_- |\psi_-\rangle |D+,N\rangle |D-,Y\rangle \quad (2)$$

Note that there is no such thing as “the” detector in this state; instead at the end of the experiment there are two versions of each detector. Since both versions of the detectors simultaneously detect their respective outcomes, there is surely no *probability* of detection of one state or the other in this system. And there is obviously no probability of existence of one or the other version of reality.

3. Particle and two detectors plus recorder. Suppose in our attempt to obtain a probability we add a recorder that reads and records the values on the two detectors. Then the entangled state, dictated by the equations of motion, is

$$|\Psi_3\rangle = a_+ |\psi_+\rangle |D+,Y\rangle |D-,N\rangle |recorder\ records\ YN\rangle + a_- |\psi_-\rangle |D+,N\rangle |D-,Y\rangle |recorder\ records\ NY\rangle \quad (3)$$

One might try to write the probability law at this stage as: The probability of “the” recorder recording result YN is $|a_+|^2$. But in QM-A, this is nonsense. First there is no “the” recorder; instead there are two simultaneously existing versions of the recorder. In addition, there is never an instance where one version records and the other doesn’t; both versions always record their respective results. So there is surely no *probability* associated with what the versions of the recorder record. Thus it is not possible to define probability—of existence, detection or recording—within QM-A in the state of equation (3).

4. The observer. Within QM-A an inanimate recorder is not, in principle, different from an observer. To emphasize this, we can rewrite equation (3) as

$$|\Psi_3\rangle = a_+ |\psi_+\rangle |D+,Y\rangle |D-,N\rangle |observer\ perceives\ YN\rangle + a_- |\psi_-\rangle |D+,N\rangle |D-,Y\rangle |observer\ perceives\ NY\rangle \quad (4)$$

Thus, in exact parallel to there being no way to define the probability of “the” recorder recording just YN , there is also no way to define the probability of “the” observer perceiving just YN . If I am the observer, “I” perceive YN on 100% of the runs and, with equal validity, a separate version of “I” simultaneously perceives NY on 100% of the runs.

Adding in the environment, the rest of physical existence, changes nothing. Thus probability—of existence, detection, recording, or perception—cannot be defined

in QM-A; it is not inherent in QM-A; it cannot be shown to be an attribute of the state in QM-A.

4. No assignment of the observer to an outcome

Because probability is not inherent in the state vector, one might conjecture that it comes instead in the “assigning” of “the” observer to a particular branch; I see YN because “I” have been “assigned” to the YN branch with a certain probability. But within QM-A, this does not work, for two reasons. First, after the experiment, and after the observer looks at the readings on the detectors, there is, in QM-A, no “the” observer to be assigned to one version of reality or the other; instead there are two equally valid, simultaneously existing versions of the observer, one associated with each version of reality. So you cannot say “I” become the YN version of the observer with such and such a probability because in the MWI, “I” become *both* the YN and the NY versions with 100% probability.

The second reason why assigning the observer to a particular branch doesn’t work is that there is no “assigning” mechanism within QM-A. All the versions are on an equal par; no version of the observer/recorder is singled out as being more “aware” or more “real” than any other.

5. The probability law is in conflict with QM-A

The arguments just given are sufficient to show there is no probability inherent in QM-A. But we can go further and show that the probability law is in conflict with the MWI.

To do this, we examine the case where the spin $\frac{1}{2}$ S-G experiment is repeated N times (N large). Because of the presumed equivalence between recorders and observers, it is sufficient to consider only recorders. (This puts the focus on the implications of QM-A and avoids the confusion that might be caused by the characteristics of our actual perceptions.) These “perceive” (by electronic means) the readings of detectors and “report” (by displaying the readings on a dial, or electronically communicating the outcomes to other devices) the results of every run. The state of the system after the N experiments, leaving out the detectors and other electronic devices, is

$$|\Psi_N\rangle = \sum_{s_1=-1/2}^{+1/2} \dots \sum_{s_N=-1/2}^{+1/2} a_+^m a_-^{N-m} |s_1\rangle \dots |s_N\rangle \quad (5)$$

$|recorder\ perceives\ and\ reports\ s_1 \dots s_N\rangle$

where m is the number of spin $+1/2$ states in $|s_1\rangle \dots |s_N\rangle$. There are 2^N different, non-interacting, non-communicating, simultaneously existing, equally valid versions of the recorder. $N!/m!(N-m)!$ of these versions record m $|+1/2\rangle$ and $(N-m)$ $| -1/2\rangle$ states. Note that the recorder, with all its dents and scratches, evolves from its single state as “the” recorder before the experiment to *all* 2^N versions of the recorder, each with the same dents and scratches, after the experiment.

Now the probability law implies that only those versions of the observer for which m is near $N |a_+|^2$ perceive and report their respective outcomes. And then because of the presumed equivalence of observers and recorders in QM-A, the probability law implies that only those versions of the *recorder* for which m is near $N |a_+|^2$ perceive and report their respective results. But this cannot be, because in QM-A *every* version of the recorder, no matter what the values of the coefficients, perceives and reports its respective outcome. That is, the acts of perceiving and reporting in the state $| \text{recorder perceives and reports } s_1 \dots s_N \rangle$ are independent of the coefficients.

Thus since the probability law says perceiving and reporting are coefficient-dependent while QM-A says they are not, there is a clear conflict between the probability law and the QM-A-based MWI. So if we define QM-B as an interpretive scheme based on the seven principles of QM-A plus the assumed probability law, that interpretive scheme is not viable because it is internally inconsistent.

To further emphasize the conflict between QM-A and the probability law, we ask the question: Since only the versions of the observer/recorder perceive, and since each version of the observer/recorder always perceives its respective outcome, what “entity” is it that perceives only those states with m near $N |a_+|^2$? The answer is that there is no such entity in QM-A.

In conclusion, if we insist on the probability law, as experiment tells us we must, then one or more of principles (1) to (7) must be abandoned. That is, either there are hidden variables, or there is collapse, or there is a fundamental difference between an observer and an electronic recording device.

6. The work of others

Everett [7], the originator of the MWI, tried to finesse the probability issue in the following way: He supposed the observer perceived only the end results, $m +$ spins and $(N - m) -$ spins. The sums of the magnitudes squared of all those states with $m +$ spins is

$$\frac{N!}{m!(N-m)!} |a_+|^{2m} |a_-|^{2(N-m)} \quad (6)$$

This has a sharp maximum, as a function of m , at $m/N = |a_+|^2$. Everett reasoned that *in the limit* as N approached infinity, all those states with $m/N \neq |a_+|^2$ would essentially disappear (be of no consequence because their norms were essentially 0). And thus the only states perceived would be those which obeyed the probability law ($m/N = |a_+|^2$). But this does not tell us why the probability law holds to good approximation for *finite* N , and hence the reasoning is insufficient.

Zurek [9-11] claims to have derived the probability law from basic quantum mechanics. But his starting point is not QM-A because he assumes probability is a property of the state vector. (This is stated in his Fact 2 in references 9 and 10: “Given the measured observable, the state of the system S is all that is needed ... to predict measurement results, including probabilities of outcomes.”) This assumption, however, is contradicted by the reasoning of section 3, which shows that there is no *a priori* concept of probability in pure linear equation, Hilbert space quantum mechanics. Further Zurek ends up at QM-B—principles (1) to (7) by (implicit) assumption and the probability law by derivation (under certain assumptions). But we have seen that QM-B does not give a consistent interpretation so Zurek’s reasoning does not lead to a viable interpretive scheme.

There have been other attempts to derive probability from basic quantum mechanics. Deutsch [12] uses decision theory while Wallace and Saunders [13,14] use subjective likelihood. But none of these can get around the arguments showing that principles (1) to (7) are incompatible with probability. In addition, I don’t believe it is possible for these authors to successfully pursue their arguments based on the premise that an observer is not different in essence from a recorder.

7. Summary

In Everett’s many-world interpretation, there are no particles or hidden variables, there is no collapse, and observers are equivalent to recorders. There are several simultaneously existing, equally valid versions of reality in the state vector, each of which contains a version of the observer.

- Each version of the observer perceives its respective outcome on every run of the experiment. Thus, because each version of the observer *always* perceives, surely the perceptions of the versions of the observers do not obey the probability law.
- *Only* the versions of the observer perceive.
- There is no non-quantum-mechanical observer associated with just one version of the observer. So you cannot say “I” become version 17 of the observer with such and such a probability; in the MWI, “I” (including my physical body and memories) become *every* version of the observer with 100% probability.

These properties imply there is no perceiving entity, no “I” in the MWI whose perceptions could be governed by a probabilistic law. Thus probability of perception does not exist in the MWI. This implies the MWI is not a valid interpretation because it cannot accommodate the probability law.

Further, the scheme consisting of the principles of the MWI plus the *assumption* of probability does not give a valid interpretation because it is internally inconsistent. Therefore, to have a valid interpretation, one or more of the principles of the MWI must be abandoned; either there are hidden variables, or there is collapse, or there is a fundamental difference between an observer and an electronic recording device.

References

- [1] Bohm, D. A suggested interpretation of quantum theory in terms of “hidden variables”. *Phys. Rev.* **85**, 166-179 (1952).
- [2] Bohm, D. & Hiley, B. J. *The Undivided Universe* (Routledge, New York, 1993).
- [3] Ghirardi, G. C., Rimini, A. & Weber, T. Unified dynamics for microscopic and macroscopic systems. *Phys. Rev.* **D34**, 470-491 (1986).
- [4] Pearle, P. Combining stochastic dynamical state-vector reduction with spontaneous localization. *Phys. Rev.* **A39**, 2277-2289 (1989).
- [5] Leggett, A. J. Testing the limits of quantum mechanics: motivation, state of play, prospects. *J. Phys.: Condens. Matter* **14**, R415-R451 (2002).
- [6] Blood, C. A primer on quantum mechanics and its interpretations, *arXiv:quant-ph/1001.3080* (2010).
- [7] Everett, H. Relative state formulation of quantum mechanics. *Rev. Mod. Phys.* **29** 454-462 (1957).
- [8] Blood, C. Quantum mechanics, by itself, implies perception of a classical world. *arXiv:quant-ph/1009.4614* (2010).
- [9] Zurek, W. H. Relative states and the environment: einselection, envariance, quantum Darwinism, and the existential interpretation. *arXiv:quant-ph/0707.2832v1*, 1-27 (2007).
- [10] Zurek, W. H. Probabilities from entanglement, Born’s rule from envariance. *arXiv:quant-ph/0405161v2*, 1-32 (2004).
- [11] Zurek, W. H. Quantum Darwinism. *Nature Phys.* **5**, 181-188 (2009).
- [12] Deutsch, D. Quantum theory of probability and decisions. *Proceedings of the Royal Society of London* **A455**, 3129-3137 (1999).
- [13] Wallace, D. Quantum probability from subjective likelihood: improving on Deutsch’s proof of the probability rule. *arXiv:quant-ph/0312157v2*, 1-26 (2005).
- [14] Saunders, S. & Wallace, D. Branching and uncertainty. *British Journal for the Philosophy of Science* **59**, 293-305 (2008).