9

Many Worlds?

9.1 Alternatives to the de Broglie–Bohm Theory

A reader who would search the literature will find many different "interpretations" of quantum mechanics. For example, there is a "bibliographic guide" by the Spanish physicist Adán Cabello [37], discussing only "foundations of quantum mechanics" that contains more than 10.000 references!

Obviously we cannot discuss all of them. But they can be roughly divided into four categories, which are pretty much logical alternatives:

(1) The wave function is a complete description of any physical system and it evolves according to the usual laws, the linear evolution between observations and the collapse rule during observations. One then tries to "make sense" of this framework or to "interpret" it.
(2) One completes the wave function by adding variables (called "hidden") to the usual formalism.
(3) The wave function evolves according to laws different from the usual ones: for example, it may collapse spontaneously even when no observations are made.
(4) The wave function is the complete description of any physical system, but it always evolves according to the linear Schrödinger evolution, and never collapses.

For the reasons explained in Chap. 5, we do not think that alternative (1) can work: the linear evolution leads to macroscopic superpositions and one can

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only recover the usual description of the macroscopic reality by introducing a collapse of the wave function in an arbitrary fashion.

There are also versions of (1) that are essentially philosophical: we are urged, in order to understand quantum mechanics, to give up notions such as "objective reality". We have explained our objections to such a philosophical escape route in Chap. 6.

The de Broglie–Bohm theory is an instance of alternative (2), but there are not many other such instances: indeed, the no hidden variables theorem of Sect. 5.2 practically prevents the introduction of "hidden variables" other than positions.[1]

In option (3), one modifies the usual time evolution, outside of measurements: the wave function spontaneously collapses but in such a way that collapses are very rare for a single particle, but very frequent for macroscopic systems, such as measuring devices.[2] Then, the pointer may spontaneously go up or down, and the cat stays alive or dies spontaneously, sparing us the embarrassment of macroscopic superpositions.

But then, one necessarily obtains empirical predictions that differ in principle from those of ordinary quantum mechanics, for systems with one or few particles. Various theories of this sort have been proposed, but it should be stressed than they are not "interpretations" of quantum mechanics, but alternatives to it and that they can only be true if quantum mechanics itself is false. The theories that have been proposed depend on parameters that are chosen so that the differences between their empirical predictions for microscopic systems and those of quantum mechanics are so small that they cannot be detected with current technologies. This arbitrary choice of parameters that protects the theory against empirical refutation is not an appealing move, to say the least. But one should keep one's mind open – after all, how can we be certain that the predictions of ordinary quantum mechanics will always be correct?

Finally, one can try option (4), namely ordinary quantum mechanics, but without the collapse rule. But then, how can one reconcile this with our familiar experience of the world, where pointers are either up or down and cats are either alive or dead?

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[1] Let us mention, for the sake of completeness but without discussing them in detail, that there exists versions of alternative (2) based on "consistent histories" or "decoherent histories" that attempt to give an "objective" account of quantum mechanics, but without introducing particle trajectories, as in the de Broglie-Bohm theory. These ideas have been proposed by Murray Gell-Mann and Jim Hartle [85], Robert Griffiths [96] and Roland Omnès [136]. However, those approaches run into difficulties because of the no hidden variables theorems (see e.g. [36, Sect. 6.3] and references therein).

[2] See for example [8] for a review of such models and [36], Sect. 6.2, for a critique of them.

The answer to that question is called the many-worlds interpretation; it was introduced in 1957, in his PhD thesis, by Hugh Everett III, who was then working at Princeton University under the supervision of John Wheeler [74].

The many-worlds interpretation is nowadays a rather popular view among some physicists, particularly cosmologists, and it has a science fiction sort of attractiveness, which is why we shall discuss it in some detail.

9.2 The Many-Worlds Interpretation

The many-worlds interpretation (MWI) claims that, when the proverbial cat (or any other macroscopic body) finds itself in a superposed state, such as those discussed in Chap. 5, then, instead of having a collapse by fiat as in ordinary quantum mechanics or a collapse "in practice" as in the de Broglie–Bohm theory, both terms simply continue to exist. But how can that be possible? We always see the cat alive *or* dead but not both! The short answer is that they both exist, but in different "universes" or "worlds".[3]

Hence, whenever an experiment leads to a macroscopic superposition, the universe splits into two worlds, one for each possible result.[4] But why do I always perceive only one of the results? The answer is simple: I, meaning my body, my brain (and thus also my consciousness) becomes correlated with the states of the cat, so there are two or more copies of me also, one seeing the dead cat in one world, another seeing the live cat in another world. And that, of course, is also true for everything else: every molecule in the entire universe gets to be copied twice (maybe not instantaneously, but that is a separate question), since the two different copies of me, or of the cats, could in principle interact later with those molecules and that might affect their state.

The Israeli physicist and proponent of the many-worlds interpretation, Lev Vaidman, describes this multiplication of worlds in vivid terms:

> "I" am an object, such as the Earth, a cat, etc. "I" is defined at a particular time by a complete (classical) description of the state of my body and of my brain. "I" and "Lev" do not refer to the same things (even though my name is Lev). At the present moment there are many different "Lev"s in different worlds (not more than one in each world), but it is meaningless to say that now there is another "I". I have a particular, well defined past: I correspond to a particular "Lev" in

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[3] The reader can watch the 2012 popular presentation of the many-worlds interpretation by David Wallace called *The Long Earth: Multiverse Physics* (available at `www.youtube.com/watch?v=GRJT9qY21nA`), to see that this is indeed the way this theory is presented to a general audience.

[4] The splitting can be in more than two worlds if there are more than two possible results of the experiment: the universe splits into as many worlds as there are possible results of the experiment.

> 2012, but not to a particular "Lev" in the future: I correspond to a multitude of "Lev"s in 2022. In the framework of the MWI it is meaningless to ask: Which Lev in 2022 will I be? I will correspond to them all. Every time I perform a quantum experiment (with several possible results) it only seems to me that I obtain a single definite result. Indeed, Lev who obtains this particular result thinks this way. However, this Lev cannot be identified as the only Lev after the experiment. Lev before the experiment corresponds to all "Lev"s obtaining all possible results.
>
> Lev Vaidman [191]

Bryce DeWitt, another proponent of the many-worlds interpretation, also stresses that this multiplication of worlds has to be taken literally and not metaphorically:

> This universe is constantly splitting into a stupendous number of branches,[5] all resulting from the measurement like interactions between its myriad components. Moreover, every quantum transition taking place on every star, in every galaxy, in every remote corner of the universe is splitting our local world on earth into myriads of copies of itself.
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> Bryce S. DeWitt [56], reprinted in [57, p. 161]

To say that this view is weird is accepted by all sides. Indeed, after the passage quoted here, Bryce DeWitt also writes:

> I still recall vividly the shock I experienced on first encountering this multiworld concept. The idea of 10^{100+} slightly imperfect copies of oneself all constantly splitting into further copies, which ultimately become unrecognizable is not so easy to reconcile with common sense.
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> Bryce S. DeWitt [56], reprinted in [57, p. 161]

That last phrase might qualify as being the understatement of the century.

Note that even in his original "many-worlds" paper [75] (reprinted in [57, p. 146]), Everett stressed that "*all* elements of a superposition (all 'branches') are 'actual', none any more 'real' than the rest." Everett felt obliged to write this because "some correspondents" had written to him saying that, since we experience only one branch, we have only to assume the existence of that unique branch. This shows that some early readers of Everett were already baffled by the radical nature of the "many-worlds" proposal.

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[5] The word "branches" refers to the different worlds. (Note by J.B.).

But why am I not conscious of this proliferation of copies of myself? To explain that, one appeals to the fact, roughly explained in Sect. 8.4.3, that for macroscopic objects, wave functions corresponding to different macroscopic states do not interfere with each other, in practice at least, so that the different copies of me do not "see" each other and do not interact with each other. They could pass through the same place without having any effect on each other, since the wave functions associated to the different worlds evolve independently of each other.

Defenders of the many-worlds interpretation argue that a similar objection (about me not being conscious of those copies of myself) was raised against Copernicus and Galileo (why don't we feel the motion of the Earth around the Sun?), against Darwin (how come we are so different from apes or other animals if we have common ancestors?), and against the atomic theory of matter (how come things look full when they are mostly empty, since atoms occupy a very small part of space?), and that, in each case, science answers those objections by explaining why things look to us in certain ways, while in reality they are not as they seem. The absence, in practice, of interference between wave functions of macroscopic objects, explained in Sect. 8.4.3, is supposed to be a similar answer for this multiplication of unobservable worlds and identities.

But there are several differences between the many-worlds interpretation and those historical examples. The atomic theory made many novel predictions, and Galileo and Darwin's theories had great explanatory power (and led also later to many confirmed predictions). The many-worlds interpretation provides no new prediction and we shall argue below that, far from having great explanatory power, it has not yet been formulated in a consistent way.

The many-worlds interpretation has a sort of charm that can excite our imagination: I can imagine another world where I would be married with the woman that left me for another man, yet another world where I would have had different questions at a difficult entrance exam and would have passed it, still another one in which I would not have taken my car on the day that I had a terrible accident etc.

But these are just dreams: reality is much more complicated. The many-worlds interpretation does not give us any idea whatsoever of how many worlds there are, or what they look like. In principle, "all one has to do" is to take the wave function of the entire Universe and find how it evolves under the usual linear evolution. To put it very mildly, this is easier said than done, since we have no idea whatsoever of what the wave function of the entire Universe is.

9.3 Critique of the Many-Worlds Interpretation

Even putting aside the weirdness of the multiplication of "worlds", one must ask whether the scheme of the many-worlds interpretation is coherent. One of the main problems concerns the quantum mechanical statistical predictions. Let us make the following thought experiment. "I" decide to repeat many times a similar experiment. For example, one could send a particle towards a wall with two slits, as in the double-slit experiment, and see whether it goes through the upper or the lower slit. In the many-worlds interpretation both results (the particle goes through the upper slit and it goes through the lower one) are realized, but in different worlds. One can then repeat the same experiment with a lot of similarly prepared particles.

One may also couple these results to the proverbial cat that is alive and dead, as we did in Chap. 5. Then, in the many-worlds interpretation, after one experiment, there will be one world where the cat is alive and another one where she is dead. We putted "I" above in quotation marks, like Lev Vaidman did, because after one experiment, there will be one copy of me in one world, seeing the cat alive and another copy of me in the other world, seeing the cat dead. Let us call these two copies of me my "descendants".

Now, since I have decided to repeat the experiment, each copy of me in each world will redo it and there will be two new worlds coming out in each of the worlds already created. We shall have four worlds after two experiments, with, in each of them, a copy of myself, so that, altogether, I shall have four "descendants". And we shall have eight worlds after three experiments etc.

What will my descendants see, lets say after three experiments? One of them will see three dead cats and another one will see three cats alive. But three of them will see one cat alive and two dead cats and another three of them will see one cat dead and two alive cats.[6] That account for all eight of my descendants.

The first point to notice is that all possibilities occur. If I repeat the experiment n times (with n large, say one hundred) one of my descendants will see n dead cats and another one will see n live cats.

Suppose that the probability of having the cat alive is $\frac{1}{2}$ and of course also $\frac{1}{2}$ for the probability of having the cat dead. Now quantum mechanics predicts that if one repeats that same experiment a large number of times, one will see the cat alive approximately half of the time and one will see her dead approximately half of the time.

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[6] If there is one live cat and two dead cats, then the cat alive may occur in any one of the three successive experiments. Hence, there are three possibilities.

But then, my descendants that see the cats always alive or always dead will stop believing in quantum mechanics after a while, since their observations will be radically different from what quantum mechanics predicts.[7]

Moreover, there are also many sequences of worlds where the cats are alive approximately one quarter of the time and dead approximately three quarters of the time, and that is true for any statistics different from the cat being alive approximately half of the time and the cat being dead approximately half of the time.

So that we can be certain that many of our descendants will *not* observe the quantum predictions in their worlds.

But one could argue, on the basis of the law of large numbers (see Sect. 3.4.1) that, at least in the vast majority of worlds, the quantum predictions will be obeyed, since, in the vast majority of worlds, the frequencies will be close to $(\frac{1}{2}, \frac{1}{2})$. It is just like with coin tossing: each world splits into two worlds, one for each possible outcome, so that, after n experiments, there will be, in the vast majority of worlds, approximately $\frac{n}{2}$ worlds where the cats end up alive and approximately $\frac{n}{2}$ worlds where they end up dead.

So, in that situation, although many of my descendants will not believe in quantum mechanics after a while, because what they see contradict the quantum mechanical predictions, the vast majority of my descendants will continue to observe approximately what quantum mechanics predicts.

But what happens if, instead of being $\frac{1}{2}$ for each outcome of a single experiment, the probabilities predicted by quantum mechanics are, say, $\frac{1}{4}$ for one outcome and $\frac{3}{4}$ for the other? Then, the same use of the law of large numbers leads to the conclusion that, in the vast majority of worlds, the quantum predictions will *not* be observed, since, in those worlds, our descendants will see cats ending up alive approximately half of the time and dead also approximately half of the time, instead of the frequencies $\frac{1}{4}$ and $\frac{3}{4}$ that quantum mechanics predicts.

Another way to visualize the problem is to imagine a biased coin, with probability $\frac{3}{4}$ of falling heads and $\frac{1}{4}$ of falling tails. What sense could we make of those probabilities if we were told that both results, heads and tails, happen, but in "different worlds", each of which includes of course observers that "see" the coin being heads in one world and being tails in another world? Upon repetition of the coin tossing in each successor world, most of our descendants

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[7] The quantum probability of seeing n cats alive or n cats dead in a row is $(\frac{1}{2})^n$, since in each experiment each outcome has probability $\frac{1}{2}$. This is just like having a coin tossed n times and falling always heads or always tails.

would see the coin falling heads approximately half of the time and tails the other half.

Of course, this is also true for many people whom one might call our "cousins", namely descendants, like us, of some of our ancestors, if many identical experiments have been made in the past in each world. After all, many similar experiments are made in our world and some of them have two outcomes that do not have the same probability of one-half. So, when experiments with two outcomes whose probabilities are not both equal to one-half are performed repeatedly, the sequence of worlds in which the quantum probabilities are observed are statistically rare. So, why should I expect to belong to such a sequence of worlds?

This is *prima facie* a serious problem for the many-worlds interpretation. There have been many proposals to solve this problem but it would be too long and too technical to discuss all of them here.

One such proposal is to say that the worlds in which the quantum predictions are statistically violated have less "reality" or "intensity" or have a lower "degree of existence" than the ones in which those predictions are realized.

But although one can imagine oneself living in "another world" than the one we live in (for example, if some event that did occur in the past had not occurred), it is difficult to see what it could mean to "exist" in another world, but with a different "intensity" than the one we live in.

We already noted that, in his original paper, Everett stressed that "*all* elements of a superposition (all 'branches') are 'actual', none any more 'real' than the rest." ([75], reprinted in [57, p. 146]). But if all worlds are equally real, how come that some are less real than others?

Another proposal to solve the above-mentioned problem (a solution also going back to Everett) is to define a probability distribution on the set of worlds that is constructed so that the worlds in which the quantum mechanical predictions are violated are improbable. But that probability distribution is a pure mathematical construction that has nothing to do with the observed frequencies in the many worlds that are supposedly created.

Moreover, in all what we said above, we left out the most serious problem facing the many-worlds interpretation, namely the problem of "ontology", to use a term introduced in Sect. 5.3. Indeed we have been talking as if the worlds that multiply themselves are real worlds in our familiar three-dimensional space. But one of the selling points used by the defenders of the many-worlds interpretation is what they call the "pure wave function ontology". For them, the only thing that exists is the wave function. The motivation for adopting this idea is that it makes the many-worlds interpretation supposedly parsimonious in its ontology. Indeed, in the de Broglie–Bohm theory for example, we have both a wave function and particles whose motion is guided by the wave function, so that there are more "beings" in that world than in a world where the only being would be the wave function. Everything else being equal, ontological parsimony is obviously a virtue.[8]

But here, everything else is *not* equal. After all, the wave function is a function,[9] and a function is simply a mathematical object that associates a number to each of its arguments. But the arguments or variables that it depends on are also mathematical objects. Even if those variables characterize a cat or a pointer, saying that the wave function and only the wave function exists does not mean that cats or pointers exist in our familiar three-dimensional world. In fact, it means exactly the opposite, since the defenders of the many-worlds interpretation do *not* postulate that some of those points are material points located in our three-dimensional world, and they regard them as being just mathematical symbols.

All the wave function does is to associate a number to a set of points that would correspond to a cat or a pointer if one assumes that those points are material points, not just mathematical objects. And, if one does assume that there are material points, then the ontology would include both the wave function *and* those material points.

If one wants to make sense of the intuitive picture of the many-worlds interpretation, with actual worlds proliferating in ordinary space, then one has to add something to the ontology, besides the wave function. But then, the "ontological parsimony" argument collapses, and it is not even clear what is to be added.[10]

The many-worlds interpretation is popular among some physicists, as long as it is formulated verbally and rather loosely (All quantum possibilities coexist! There is no collapse of the wave function!). However, it remains to be seen how to formulate it in a clear way (i.e. with an explicit definition of what exists besides the wave function) and to make the quantum mechanical predictions likely to be true in the world we live in.

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[8] This is sometimes called the principle of Ockham's razor, which goes back to the scholastic philosopher William of Ockham, and according to which one should not introduce in our explanations more entities than what is necessary.

[9] As we explained in Sect. 5.3, that function depends in general on several parameters. If one considers the wave function of the Universe, that function is defined on an incredibly large number of parameters, and, if one includes fields in our description, that number is infinite.

[10] See [2] for a clear addition of an explicit ontology that gives a meaning to the many-worlds interpretation, but done by people who are not supporters of the many-worlds interpretation.

9.4 Summary

Among the multitude of "interpretations" of quantum mechanics (most of which however fall in one of the four categories of Sect. 9.1), we chose to discuss a particularly popular one: the many-worlds interpretation. In that interpretation, there is never any collapse of the wave function; every outcome of every experiment is realized, but in parallel universes, that are endlessly proliferating, with everything, including us humans, being copied in each such "world".

This theory has a certain appeal because it seems to eliminate the measurement problem without modifying the ordinary quantum evolution of the wave function and without introducing "hidden variables".

But we showed in the previous section that it cannot account in a natural way for the observed quantum statistics, for two reasons: first, all possible outcomes of all experiments ever done are realized in some worlds so that, there will always be many sequences of worlds in which the quantum predictions are not observed.

Moreover, in many situations (whenever an experiment has two outcomes that do not have the same probabilities), it is in the vast majority of worlds that the quantum predictions will not be observed. So that the quantum mechanical predictions become extremely improbable and therefore the many-worlds interpretation does not offer a plausible explanation of why they are observed in the world we live in, which is the only one we are conscious of.

Finally, the deeper problem of the many-worlds interpretation is the one of "ontology": the defenders of that interpretation like to say that all there is in the world is the wave function (of the Universe). But if that was the case, then there would be no pointers, no cats, no humans, since these "objects" are situated in our familiar three dimensional space and, at best, the wave function would induce a certain probability for those objects to be here or there, but, in an ontology where there is only the wave function, these objects simply do not exist and therefore attributing a probability to their (non-existing) positions does not make sense.