THE EVERETT INTERPRETATION OF QUANTUM MECHANICS BRYCE S. DEWITT PART IV. QUANTUM REALITY: EXPERIMENT pdf

1: Science and Ultimate Reality : John D. Barrow :

The many-worlds interpretation is an interpretation of quantum mechanics that asserts the objective reality of the universal wavefunction and denies the actuality of wavefunction collapse. Many-worlds implies that all possible alternate histories and futures are real, each representing an actual "world" (or "universe").

References and Further Reading 1. Preamble Before beginning to survey the various ways philosophers have attempted to interpret Everett, we must address the question of whether or not there even are rival interpretations of Everett. Someone might be right or wrong about the Everett interpretation â€” they might be right or wrong about whether it succeeds in explaining the experimental results of quantum mechanics, or in describing our world of macroscopically definite objects, or even in making sense â€” but there cannot be multiple logically possible Everett interpretations any more than there are multiple logically possible interpretations of molecular biology or classical electrodynamics The arguments Deutsch and Wallace provide may be persuasive to some readers. Again see Barrett , Barrett and Byrne , and Bevers So whether or not a version of the MWI is the correct interpretation of Everett, or even the only interpretation of Everett, is a question that can be adjudicated in other venues. There is one other debate that ought to be considered before embarking on our project. And that is the debate over the appropriate way to explain the results of quantum mechanical experiments. Whether or not the unitary dynamics proposed by Everett are the correct laws for describing the world is a question that is far from decided. But as this article is concerned with the question of Everett interpretation, a full rehearsal of this debate goes beyond its scope. There is no assumption made here about what the correct theory of the world is; rather there is only a historical discussion of the way people have interpreted Everett. If an atom decays the Geiger counter will click which causes the hammer to fall, the flask to break, the cyanide gas to be released and the cat to die. If an atom does not decay, the cat remains alive. Superpositions are states of systems that are represented mathematically by a weighted sum of the possible values for the property in question. Each summand will represent one of the possible values for the property and will be accompanied by a complex number coefficient which, when it is multiplied by its complex conjugate and the result is squared in other words, when its norm is squared , the standard interpretation takes to be the probability of the system collapsing into that value for the property. We never seem to observe cats or any other macroscopic objects as being in superpositions. The standard interpretation assumes that when an observer interacts with a system, that observation causes a collapse of the superposition, and the objects in the system take on definite values for the property being measured. Now we can transition from cats to electrons. These values are mutually exclusive in the sense that if an electron has a definite value for one of the properties, it does not have a definite value for any of the others. It has been experimentally determined that when electrons have a definite spin property along one axis, they are in a superposition of having spin up and spin down along both of the other axes. So, for example, when an electron is determinately x-spin up, it is in a superposition of being y-spin up and y-spin down, and it is in a superposition of being z-spin up and z-spin down. The standard interpretation tells us that when we observe electrons that are in such superpositions, they instantaneously and randomly collapse from the superposition they were in to one of the definite properties that make up that superposition. So when we take an electron that is x-spin up, for example, and measure its z-spin, the standard interpretation tells us that it collapses from being in a superposition of being z-spin up and z-spin down into either being z-spin up or being z-spin down. In the standard interpretation, this collapse explains the determinate measurement records that we get in experiments with quantum mechanical systems. The standard interpretation also tells us that if we do not observe quantum particles, then that collapse will not happen and they will remain in their superpositions. The difference in these empirical results is captured in two of the laws that are part of the theory of quantum mechanics: When no measurement, or other observation, is made of a system, then that system evolves in a deterministic and linear fashion. When a measurement, or other observation, is made of a system, then that system instantaneously and non-deterministically collapses into a definite value for the property being measured. In the standard interpretation, the second law accounts for the fact that when we measure any property of an object, it has a definite value. These two laws are not compatible, and there is no clear explanation of when one is to be used instead of the other. In other words, there is no explanation of what constitutes an act of observation in the standard interpretation. In addition to this, there is the problem that if we take measurement devices to be physical systems like any other, then the standard interpretation says that the quantum system that makes up the measuring device will evolve deterministically, but the second law says that it will take on a definite value with a certain probability. In other words, it would have to follow both a deterministic law and a law governed by chance. This is not logically possible. This, in short, is the quantum measurement problem. It is part of what has driven the search for different interpretations of quantum mechanics. Another part of what drove the search for a new interpretation of quantum mechanics was an interest in being able to apply quantum mechanics to the entire universe. This is what, at least in part, led Hugh Everett III to suggest that instead of having two mutually incompatible laws for the description of the evolution of states, we drop the law that is used when systems are observed Everett a, b. One difficulty with no-collapse theories is making sense of how it is that we seem to have determinate measurement records for quantum particles even though those particles do not have a determinate value for the property measured, since they never collapse out of their superpositions. Another is the question of probability in a universe in which everything happens. Various interpretations of Everett have answered these issues differently. It is to a discussion of these various interpretations that we now turn. When we want to learn the value of a property for some system, we measure for that property. But Everett treats measuring devices just as he would any other system with which the object system interacts, and so the measuring device will become correlated with the system that it is measuring. In order to learn anything about one subsystem, even the reading on a measuring device, one must make reference to the complement of the subsystem: As a result of the [measurement] interaction the state of the measuring apparatus is no longer capable of independent definition. It can be defined only relative to the state of the object system. In other words, there exists only a correlation between the two states of the two systems. It seems as if nothing can ever be settled by such a measurement. There is no longer any independent system state or observer state, although the two have become correlated in a one-one manner Everett b: In fact, one can settle matters with the use of relative states: To any arbitrarily chosen state for one subsystem there will correspond a unique relative state for the remainder of the composite system. This relative state will usually depend upon the choice of state for the first subsystem. Thus the state of one subsystem does not have an independent existence, but is fixed only by the state of the remaining subsystem. In other words, the states occupied by the subsystems are not independent, but correlated. Such correlations between systems arise whenever systems interact Everett b: Consider again what happens when we measure the z-spin of an x-spin up electron. Before the measurement interaction, the state of the system consisting of the electron, e, and the measuring device, m, can be expressed in this way: When we measure the z-spin, the measuring device interacts with the system it is measuring and becomes a part of the system. After that interaction, the state of the system that consists of the measuring device and the electron can be expressed in this way: In this state, the measuring device is in a superposition of reading z-spin up and z-spin down. So the way we get an explanation of our determinate measurement records is by understanding that they are records of relative states of a system. Using the concept of relative states, we can say two things: Let us say that there is a reliable observer who is about to measure the z-spin of an x-spin up electron. Let us also say that our observer is truthful. Recall that x-spin up electrons are in a superposition of being z-spin up and z-spin down. So when we describe the state of the electron mathematically there will be one summand that describes the electron as z-spin up and one that describes it as z-spin down. What this means is that where once we had a system that consisted of just an electron, there is now a system that consists of the electron and the observer. This is strange because he did not in fact get a determinate measurement record; he instead recorded a superposition of two outcomes. Everett believed he had explained determinate experience through the use of relative states

Everett b: That he did not succeed is largely agreed upon in the community of Everettians. So, if the problem is to explain how we end up with determinate measurement results, the bare theory does not provide us with that explanation. For more on the bare theory see Albert and Loewer , Albert and Barrett That Everett was uninterested in the philosophical implications of his work has been argued by Barrett , Barrett and Byrne and Bevers , though Deutsch and Wallace differ with this conclusion. To see what motivates this, consider what happens when an observer goes from being ready to read the result on a measuring device: If the observer forms beliefs about the z-spin of the electron based on the results of the experiment as it seems reasonable to presume , then the state of the system that now contains the observer will be the following: This state of the system implies that our observer is in a superposition of belief states Albert and Loewer, He feels like he has a definite result for the z-spin measurement of the electron. Albert and Loewer begin by supposing that mental states supervene on particular brain states and are accurately accessible to introspection Albert and Loewer do not explain this supervening relation; they merely state it as a given fact. But, they argue, this fact is inconsistent with taking our observer to be reliable and to his holding the belief that there was a determinate measurement record obtained when he measured the z-spin of an x-spin up electron. But our observer does not believe that the electron is z-spin up, nor does he believe that it is z-spin down since his brain is not in the state that corresponds to either of those beliefs; his brain is in a superposition of states Albert and Loewer, So Albert and Loewer give up the connection between brain states and belief states. The first way they explain this is with what they call the single mind view. In the state expressed by 4 , our observer starts out with no beliefs about the z-spin of the electron. The association of belief states with physical states is dictated by probability and is determined by the quantum evolution of the system that consists of him, the electron and the measuring device Albert and Loewer, Thus, mental states are never in superpositions, even if physical brain states are. Albert and Loewer immediately recognized certain problems with this view Jeffrey Barrett describes this problem nicely There is nothing in the dynamics proposed by Albert and Loewer that prevents the mental states of each observer from being associated with the same term or from being associated with different terms. But there is nothing that tells us which is the case. In each term of 7 there is a physical brain state for each observer, but with only one is there a mental state for each observer. Thus, it is possible that observer 1 is associated with the first term of 7 and observer 2 is associated with the second, but that neither of them realizes it. The same will hold true, mutatis mutandis, for observer 2. There is no way to determine whether or not one is speaking to a mindless hulk rather than a set of physical states with which there is associated a mental state Barrett, Barrett also points out that the single minds view predicts that when an observer repeats a measurement she may get a different result from what she first got and falsely remember having gotten a first measurement that matches her second So this observer is in a position where she cannot trust that what she remembers is what actually happened. Consider again the state represented in 4. If our observer were to repeat her measurement of the z-spin of the electron, then the second measurement would be identical to the first.

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2: What really happens in SchrÃ¶dingerâ€™s box? | Aeon Essays

The first published version of Everett's dissertation began to gain popularity when it was reprinted in The Many Worlds Interpretation of Quantum Mechanics (DeWitt and Graham). In his papers in this volume, DeWitt explicitly refers to the "reality of all simultaneous worlds" that he believes are implied by his reading of Everett and to.

Introduction Everett developed his relative-state formulation of quantum mechanics while a graduate student in physics at Princeton University. His doctoral thesis a was accepted in March and a paper b covering essentially the same material was published in July of the same year. The published version was revised from a longer draft thesis that Everett had given John Wheeler, his Ph. Everett took a job outside academics as a defense analyst in the spring of While subsequent notes and letters indicate that he continued to be interested in the conceptual problems of quantum mechanics and, in particular, in the reception and interpretation of his formulation of the theory, he did not take an active role in the debates surrounding either. Consequently, the long version of his thesis is the most complete description of his theory. Everett died in The result was his relative-state interpretation of pure wave mechanics. Indeed, it is fair to say that most no-collapse interpretations of quantum mechanics have at one time or another either been directly attributed to Everett or suggested as charitable reconstructions. The most popular of these, the many worlds interpretation, is often simply attributed to Everett directly and without comment even when Everett himself never characterized his theory in terms of many worlds. The Measurement Problem Everett presented his relative-state formulation of pure wave mechanics as a way of avoiding conceptual problems encountered by the standard von Neumann-Dirac collapse formulation of quantum mechanics. The main problem, according to Everett, was that the standard collapse formulation of quantum mechanics, like the Copenhagen interpretation, required observers always to be treated as external to the system described by the theory. One consequence of this was that neither the standard collapse theory nor the Copenhagen interpretation can be used to describe the physical universe as a whole. He took the von Neumann-Dirac collapse theory to be inconsistent and the Copenhagen interpretation to be essentially incomplete. In order to understand what Everett was worried about, one must first understand how the standard collapse formulation of quantum mechanics works. The theory involves the following principles von Neumann, More specifically, the probability of ending up in a particular final state is equal to the norm squared of the projection of the initial state on the final state. While he took the standard collapse theory to encounter a serious conceptual problem, he also used it as the starting point for his presentation of pure wave mechanics, which he described as the standard collapse theory but without the collapse dynamics rule 4b. According to the eigenvalue-eigenstate link rule 3 a system would typically neither determinately have nor determinately not have a particular given property. In order to determinately have a particular property the vector representing the state of a system must be in the ray or subspace in state space representing the property, and in order to determinately not have the property the state of a system must be in the subspace orthogonal to it, and most state vectors will be neither parallel nor orthogonal to a given ray. The deterministic dynamics rule 4a typically does nothing to guarantee that a system will either determinately have or determinately not have a particular property when one observes the system to see whether the system has that property. This is why the collapse dynamics rule 4b is needed in the standard formulation of quantum mechanics. It is the collapse dynamics that guarantees that a system will either determinately have or determinately not have a particular property by the lights of rule 3 whenever one observes the system to see whether or not it has the property. But the linear dynamics rule 4a is also needed to account for quantum mechanical interference effects. So the standard theory has two dynamical laws: But the standard formulation of quantum mechanics does not say what it takes for an interaction to count as a measurement. Without specifying this, the theory is at best incomplete since it does not indicate when each dynamical law obtains. Moreover, if one supposes that observers and their measuring devices are constructed from simpler systems that each obey the deterministic dynamics, as Everett did, then the composite systems, the observers and their measuring devices, must evolve in a continuous deterministic way, and nothing like the random, discontinuous evolution described by rule 4b can ever occur. That is, if observers and their measuring devices are understood as being constructed of simpler systems each behaving as quantum mechanics requires, each obeying rule 4a, then the standard formulation of quantum mechanics is logically inconsistent since it says that the two systems together must obey rule 4b. This is the quantum measurement problem in the context of the standard collapse formulation of quantum mechanics. See the section on the measurement problem in the entry on philosophical issues in quantum theory. The problem with the theory, Everett argued, was that it was logically inconsistent and hence untenable. In particular, one could not provide a consistent account of nested measurement in the theory. Everett was careful, however, to explain why this was entirely irrelevant to the conceptual problem at hand. If he merely believes that the system is described by a state function, which he does not presume to know, then the difficulty still exists. In particular, Everett held that one only has a satisfactory solution to the quantum measurement problem if one can provide a consistent account of nested measurement. Everett called the theory pure wave mechanics. He believed that he could deduce the standard statistical predictions of quantum mechanics the predictions that depend on rule 4b in the standard collapse formulation of quantum mechanics in terms of the subjective experiences of observers who are themselves treated as ordinary physical systems within pure wave mechanics. Everett described the proposed deduction in the long thesis as follows: We shall be able to introduce into [pure wave mechanics] systems which represent observers. Such systems can be conceived as automatically functioning machines servomechanisms possessing recording devices memory and which are capable of responding to their environment. The behavior of these observers shall always be treated within the framework of wave mechanics. Furthermore, we shall deduce the probabilistic assertions of Process 1 [rule 4b] as subjective appearances to such observers, thus placing the theory in correspondence with experience. We are then led to the novel situation in which the formal theory is objectively continuous and causal, while subjectively discontinuous and probabilistic. While this point of view thus shall ultimately justify our use of the statistical assertions of the orthodox view, it enables us to do so in a logically consistent manner, allowing for the existence of other observers , 77â€”8. More specifically, he wanted to show that observers, modeled as servomechanisms within pure wave mechanics, would have fully determinate relative measurement records and the probabilistic assertions of the standard theory will correspond to statistical properties of typical sequences of such relative records. The main problem in understanding what Everett had in mind is in figuring out precisely how the correspondence between the predictions of the standard collapse theory and the pure wave mechanics was supposed to work. Part of the problem is that the former theory is stochastic with fundamentally chance events and the latter deterministic with no mention of probabilities whatsoever, but there is also a problem even accounting for determinate measurement records in pure wave mechanics. More specifically, here the standard collapse theory predicts that on measurement the quantum-mechanical state of the composite system will collapse to precisely one of the following two states: Everett, then, faced two closely related problems. The determinate-record problem requires him to explain how a measurement interaction like that just described might yield a determinate record in the context of pure wave mechanics. And the probability problem requires him to somehow recover the standard quantum statistics for such determinate records. Everett took the key to the solution of both problems to be the principle of the fundamental relativity of states: There does not, in general, exist anything like a single state for one subsystem of a composite system. Subsystems do not possess states that are independent of the states of the remainder of the system, so that the subsystem states are generally correlated with one another. One can arbitrarily choose a state for one subsystem, and be led to the relative state for the remainder. Thus we are faced with a fundamental relativity of states, which is implied by the formalism of composite systems. It is meaningless to ask the absolute state of a subsystemâ€”one can only ask the state relative to a given state of the remainder of the subsystem. The resulting theory is the relative-state formulation of pure wave mechanics. Central to this theory is the distinction between absolute and relative states. This distinction played an essential explanatory role for Everett. Let one regard an observer as a subsystem of the composite system: It is then an inescapable consequence that after the interaction has taken place there will not, generally, exist a single observer state. There will, however, be a superposition of the composite system states, each element of which contains a definite observer state and a definite relative object-system state. Furthermore, as we shall see, each of these relative object system states will be, approximately, the eigenstates of the observation corresponding to the value obtained by the observer which is described by the same element of the superposition. Thus, each element of the resulting superposition describes an observer who perceived a definite and generally different result, and to whom it appears that the object-system state has been transformed into the corresponding eigenstate. Absolute states, then, provide absolute properties for complete composite systems by way of the standard eigenvalue-eigenstate link, and relative states provide relative properties for subsystems of a composite system. Why this was enough to fully explain our experience of determinate measurement records ultimately rests on his understanding what it means for a physical theory to be empirically faithful. The whole state vector It contains all possible branches in it at the same time. In the real physical world we must be content with just one branch. Barrett and Byrne , â€”7 The thought was that the richness of pure wave mechanics indicated an empirical flaw in the theory because we do not notice other branches. As DeWitt put it: The trajectory of the memory configuration of a real observer I can testify to this from personal introspection, as can you. I simply do not branch. Barrett and Byrne eds , Wheeler showed Everett the letter and told him to reply. In his 31 May letter to DeWitt, Everett began by summarizing his understanding of the proper cognitive status of physical theories. First, I must say a few words to clarify my conception of the nature and purpose of physical theories in general. To me, any physical theory is a logical construct model , consisting of symbols and rules for their manipulation, some of whose elements are associated with elements of the perceived world. If this association is an isomorphism or at least a homomorphism we can speak of the theory as correct, or as faithful. The fundamental requirements of any theory are logical consistency and correctness in this sense. The map is a homomorphism because 1 there may be elements of the theory that do not directly correspond to experience and because 2 a particular theory may not seek to explain all of experience. It is case 1 that is particularly important here: Everett considered the surplus experiential structure represented in the various branches of the absolute state to be explanatorily harmless. In his letter to DeWitt, Everett described how he understood the aim of physical inquiry: The task then was to find our experience in an appropriate way in the relative-state model of pure wave mechanics. So, for Everett, a theory was empirically faithful and hence empirically acceptable if there was a homomorphism between its model and the world as experienced. In short, Everett took pure wave mechanics to be empirically faithful because one could find quantum mechanical experience in the model as relative memory records associated with relative modeled observers. Four Arguments Together the following four arguments indicate the sense in which Everett took pure wave mechanics to be empirically faithful and, hence, to recapture the empirical predictions of the standard collapse theory. This is also true in the theory if one only relatively, rather than absolutely, makes the sequence of observations. In this precise sense, then, it is possible to find our experience as sequences of relative records in the model of pure wave mechanics. Everett took such relative records to be sufficient to explain the subjective appearances of observers because in an ideal measurement, every relative state will be one where the observer in fact has, and, as we will see in the next section, would report that she has, a fully determinate, repeatable measurement record that agrees with the records of other ideal observers. As Everett put it, the system states observed by a relative observer are eigenstates of the observable being measured , Note that Everett did not require a physically preferred basis to solve the determinate record problem to show that pure wave mechanics was empirically faithful. The principle of the fundamental relatively of states explicitly allows for arbitrarily specified decompositions of the absolute universal state into relative states. Given his understanding of empirical faithfulness, all Everett needed to explain a particular actual record was to show that is that there is some decomposition of the state that represents the modeled observer with the corresponding relative record. And he clearly has that in pure wave mechanics under relatively weak assumptions regarding the nature of the actual absolute quantum mechanical state. There are two distinct arguments that Everett seems to have had in mind.

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3: McCabism: Science and Ultimate Reality

While he was initially skeptical of Everett's views, DeWitt became an ardent proponent of the many-worlds interpretation, a theory that DeWitt presented as the EWG interpretation of quantum mechanics after Everett, Wheeler, and DeWitt's graduate student R. Neill Graham.

Support Aeon Donate now In , Ernest Rutherford, Hans Geiger and Ernest Marsden took a piece of radium and used it to fire charged particles at a sheet of gold foil. Instead of whooshing straight through the thin soup of electrons that should have been all that hovered in their path, the particles had encountered something solid enough to push back. Something was wrong with matter. Somewhere, reality had departed from the best available model. The first big insight came from Rutherford himself. He realised that, if the structure of the atom were to permit collisions of the magnitude that his team had observed, its mass must be concentrated in a central nucleus, with electrons whirling around it. Could such a structure be stable? Such concerns prompted the Danish physicist Niels Bohr to formulate a rather oddly rigid model of the atom, using artificial-seeming rules about electron orbits and energy levels to keep everything in order. It was ugly but it seemed to work. Physical theory might have recovered some grip on reality but it seemed to have decisively parted company from common sense. By , these disparate intuitions and partial models were already unified into a new mathematical theory called quantum mechanics. Within a few years, the implications for chemistry, spectroscopy and nuclear physics were being confirmed. It was clear from the start that quantum theory challenged all our previous preconceptions about the nature of matter and how it behaves, and indeed about what science can possibly â€” even in principle â€” say about these questions. Over the years, this very slipperiness has made it irresistible to hucksters of various descriptions. I regularly receive ads offering to teach me how to make quantum jumps into alternate universes, tap into my infinite quantum self-energy, and make other exciting-sounding excursions from the plane of reason and meaning. Quantum mechanics has correctly predicted the outcomes of a vast range of investigations, from the scattering of X-rays by crystals to the discovery of the Higgs boson at the Large Hadron Collider. It successfully explains a vast range of natural phenomena, including the structure of atoms and molecules, nuclear fission and fusion, the way light interacts with matter, how stars evolve and shine, and how the elements forming the world around us were originally created. Einstein in particular never quite accepted it. Given apparently sensible demands on what a description of physical reality must entail, it seemed that something must be missing. We needed a deeper theory to understand physical reality fully. Einstein never found the deeper theory he sought. Indeed, later theoretical work by the Irish physicist John Bell and subsequent experiments suggested that the apparently reasonable demands of that paper could never be satisfied. Had Einstein lived to see this work, he would surely have agreed that his own search for a deeper theory of reality needed to follow a different path from the one he sketched in Even so, I believe that Einstein would have remained convinced that a deeper theory was needed. None of the ways we have so far found of looking at quantum theory are entirely believable. To be ruthlessly honest, none of them even quite makes sense. But that might be about to change. While the mathematics of quantum theory works very well in telling us what to expect at the end of an experiment, it seems peculiarly conceptually confusing when we try to understand what was happening during the experiment. To calculate what outcomes we might expect when we fire protons at one another in the Large Hadron Collider, we need to analyse what â€” at first sight â€” look like many different stories. The same final set of particles detected after a collision might have been generated by lots of different possible sequences of energy exchanges involving lots of different possible collections of particles. You just reason that, of all the people who could have brought them, one of them presumably did. We get a mathematical recipe that tells us to combine, in an elegant but conceptually mysterious way, numbers attached to each possible explanation. Then we use the result of this calculation to work out the likelihood of any given final result. Unlike the mathematical theory of probability, this quantum recipe requires us to make different possible stories cancel each other out, or fully or partially reinforce each other. This means that the net chance of an outcome arising from several possible stories can be more or less than the sum of the chances associated with each. To get a sense of the conceptual mystery we face here, imagine you have three friends, John, Mary and Jo, who absolutely never talk to each other or interact in any other way. Pretty precisely analogous things happen in quantum experiments. According to this approach, a scientific question makes sense only if we have a direct way of verifying the answer. The Copenhagen interpretation was very much in line with the scientific philosophy of logical positivism that caught on at around the same time. To some of the founders of quantum theory, as well as to later adherents of the Copenhagen interpretation, this came to seem an almost self-evident description of the scientific process. Even after philosophers largely abandoned logical positivism â€” not least because the principle of verification fails its own test for meaningful statements â€” many physicists trained in the Copenhagen tradition insisted that their stance was no more than common sense. However, its consequences are far from commonsensical. Insofar as we learnt anything about nature from the Large Hadron Collider, it was merely what sort of records you get in your detectors when you build something like the Large Hadron Collider. Quantum theory is supposed to describe the behaviour of elementary particles, atoms, molecules and every other form of matter in the universe. This includes us, our planet and, of course, the Large Hadron Collider. In that sense, everything since the Big Bang has been one giant quantum experiment, in which all the particles in the universe, including those we think of as making up the Earth and our own bodies, are involved. Only at the end, when we might perhaps imagine some technologically advanced alien experimenters in the future looking at the final state of the universe, can any meaningful statement be made. Of course, this final observation will never happen. By definition, no one is sitting outside the universe waiting to observe the final outcome at the end of time. Our most fundamental scientific theory turns out to be a threat to the whole enterprise of science. For these and related reasons, the Copenhagen interpretation gradually fell out of general favour. Its great rival was first set out in a paper and Princeton PhD thesis written by one of the stranger figures in the history of 20th-century physics, Hugh Everett III. Rather unromantically, and very unusually for a highly original thinker and talented physicist, Everett abandoned theoretical physics after he had published his big idea. One way of thinking about his ideas on quantum theory is that our difficulties in getting a description of quantum reality arise from a tension between the mathematics â€” which, as we have seen, tells us to make calculations involving many different possible stories about what might have really happened â€” and the apparently incontrovertible fact that, at the end of an experiment, we see that only one thing actually did happen. This led Everett to ask a question that seems at first sight stupid, but which turns out to be very deep: What if we take the hint from the mathematics and consider a picture of reality in which many different things actually do happen â€” everything, in fact, that quantum theory allows? And what if we take this to its logical conclusion and accept the same view of cosmology, so that all the different possible histories of the evolution of the universe are realised? On this view, every time any of us does a quantum experiment with several possible outcomes, all those outcomes are enacted in different branches of reality, each of which contains a copy of our self whose memories are identical up to the start of experiment, but each of whom sees different results. None of these future selves has any special claim to be the real one. They are all equally real â€” genuine but distinct successors of the person who started the experiment. The same picture holds true more generally in cosmology: To such a gibe, Everett and his followers would reply that science has taught us many things that seemed incredible at first. But to this, too, Everettians have an answer: The many worlds are there in the equations. Everettians might have a point, then, when they argue that their ideas deserve a hearing. The problem is that, from Everett and his early followers onwards, they have never managed to agree on a clear story about how exactly this picture of branching worlds is supposed to emerge from the fundamental equations of quantum theory, and how this single world that we see, with experimental outcomes that are apparently random but which follow definite statistical laws, might then be explained. Although generally in more civil terms, Everettians have continued to argue over this and related points ever since. Indeed, the big unresolved, and seemingly unsolvable, problem here is how statistical laws can possibly emerge at all when the Everettian meta-picture of branching worlds has no randomness in it. Everettians continue to devote much ingenuity to deriving statements involving probabilities from the underlying deterministic many-worlds picture. One idea lately advocated by David Deutsch and David Wallace of the University of Oxford is to try to use decision theory, the area of mathematics that concerns rational decision-making, to explain how rational people should behave if they believe they are in a branching universe. Deutsch and Wallace start from a few purportedly simple and natural technical assumptions about the preferences one should have in a branching world and then claim to show that rational Everettians should behave as though they were in an uncertain probabilistic world following the statistical laws of quantum theory, even though they believe their true situation is very different. One problem with this line of thought is that the assumptions turn out not to seem especially natural, or even properly defined, on close inspection. The easiest way to understand this is to look for rationally defensible strategies for life in a branching universe other than the ones Deutsch and Wallace advocate. One example I rather like because it makes the point succinctly, not because it seems morally attractive is that of future self elitism, which counsels us to focus only on the welfare of our most fortunate and successful future successor, perhaps on the premise that our best possible future self is our truest self. The key scientific question is why the experimental evidence for quantum theory justifies a belief in many worlds in the first place. Many Everettians â€” from Everett and DeWitt onwards â€” have tried to give a satisfactory answer to this. Many critics myself included appreciate the cunning of their attempts but think they have all failed. If we cannot get a coherent story about physical reality from the Copenhagen interpretation of quantum theory and we cannot get a scientifically adequate one from many-worlds theory, where do we turn? We could, as some physicists suggest, simply give up on the hope of finding any description of an objective external reality. But it is very hard to see how to do this without also giving up on science. The hypothesis that our universe began from something like a Big Bang, our account of the evolution of galaxies and stars, the formation of the elements and of planets and all of chemistry, biology, physics, archaeology, palaeontology and indeed human history â€” all rely on propositions about real observer-independent facts and events. Once we assume the existence of an external world that changes over time, these interrelated propositions form a logically coherent set; chemistry depends on cosmology, evolution on chemistry, history on evolution and so on. Without that assumption, it is very hard to see how one might make sense of any of these disciplines, let alone see a unifying picture that underlies them all and explains their deep interrelations and mutual dependence. Physics poses many puzzles, and the focus of the physics community shifts over time. Most theoretical physicists today do not work on this question about what really happens in quantum experiments. Among those who think about it at all, many hope that we can find a way of thinking about quantum theory in which reality somehow evaporates or never arises. That seems like wishful thinking to me. The alternative, as John Bell recognised earlier and more clearly than almost all of his contemporaries, is to accept that quantum theory cannot be a complete fundamental theory of nature. As mentioned above, Einstein also believed this, though at least partly because of arguments that Bell was instrumental in refuting. On this view, which was once as close to heresy as a scientific argument can be but is now widely held among scientists who work on the foundations of physics, the reality problem is just not solvable within quantum theory as it stands. Bell coined the term beables to refer to these elusive missing ingredients. And indeed it turns out that we can extend quantum theory to include beables that would directly describe the sort of reality we actually see. Some of the most interesting work in fundamental physics in the past few decades has been in the search for new theories that agree with quantum theory in its predictions to date, but which include a beable description of reality, and so give us a profoundly different fundamental picture of the world. What sort of quantities might do the trick? One early idea comes from Louis de Broglie, whom we met earlier, and David Bohm, an American theoretical physicist who fled McCarthyite persecution and spent most of his career at the University of London. The essence of their proposal is that, in addition to the mathematical quantities given to us by quantum theory, we also have equations defining a definite path through space and time for each elementary particle in nature. It does, however, very much violate its spirit, as well as the beautiful symmetry principles incorporated in the underlying mathematics. In the s, a much more promising avenue opened up, thanks to the efforts of Giancarlo Ghirardi, Alberto Rimini, Tullio Weber and Philip Pearle, three European theorists and an American. As we have already noted, the tension between these two descriptions is at the heart of the quantum reality problem.

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BRYCE S. DEWITT Schrddinger's cat. The animal trapped in a room together with a Geiger counter and a hammer, which, upon discharge of the counter, smashes a flask af prussic acid.

John Archibald Wheeler and the clash of ideas Paul C. The heritage of Heraclitus: Quantum Reality - Theory: Why is nature described by quantum theory? Thought experiments in honor of John Wheeler Freeman J. It from qubit David Deutsch; 6. Quantum Darwinism and envariance Wojciech H. Using qubits to learn about it Juan Pablo Paz; 9. Quantum gravity as an ordinary gauge theory Juan M. The Everett interpretation of quantum mechanics Bryce S. Quantum Reality - Experiment: Three far-reaching, visionary questions from John Archibald Wheeler and how they inspired a quantum experimentalist Anton Zeilinger; Speakable and unspeakable, past and future Aephraim M. Conceptual tensions between quantum mechanics and general relativity: Quantum erasing the nature of reality - or, perhaps, the reality of nature? Kwiat and Berthold-Georg Englert; Quantum feedback and the quantum-classical transition Hideo Mabuchi; What quantum computers may tell us about quantum mechanics Christopher R. Big Questions in Cosmology: Cosmic inflation and the arrow of time Andreas Albrecht; Cosmology and immutability John D. Quantum cosmology, inflation, and the anthropic principle Andrei Linde; Parallel universes Max Tegmark; Quantum theories of gravity: A genuinely evolving universe Joao Magueijo; Planck-scale models of the universe Fotini G. Emergence, Life, and Related Topics: True complexity and its associated ontology George F. Autonomous agents Stuart A. Science and ultimate reality program committees; Appendix B. Young researchers competition in honor of John Archibald Wheeler for physics graduate students, post-doctoral fellows, and young faculty. Reviews "This is theoretical physics at its best. His inimitable style of thinking, quirky wit, and love of the bizarre have inspired generations of physicists. He was a remarkable man and this is a remarkable volume. I can only imagine that this book will be read by more great minds eager to plunge into the darkness to shed some light with a torch or even star.

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DeWitt's solution, for which he credits Everett, was that quantum theory describes everything including the experimental apparatus and even the scientist who performs the experiment.

He went on to assert that what the equation that won him a Nobel prize seems to be describing is several different histories, they are "not alternatives but all really happen simultaneously". This is the earliest known reference to the many-worlds. The many-worlds interpretation shares many similarities with later, other "post-Everett" interpretations of quantum mechanics which also use decoherence to explain the process of measurement or wavefunction collapse. MWI treats the other histories or worlds as real since it regards the universal wavefunction as the "basic physical entity" [20] or "the fundamental entity, obeying at all times a deterministic wave equation". MWI is distinguished by two qualities: Decoherent interpretations of many-worlds using einselection to explain how a small number of classical pointer states can emerge from the enormous Hilbert space of superpositions have been proposed by Wojciech H. Other states decohere into mixtures of stable pointer states that can persist, and, in this sense, exist: Many-worlds is often referred to as a theory , rather than just an interpretation, by those who propose that many-worlds can make testable predictions such as David Deutsch or is falsifiable such as Everett or by those who propose that all the other, non-MW interpretations, are inconsistent, illogical or unscientific in their handling of measurements; Hugh Everett argued that his formulation was a metatheory , since it made statements about other interpretations of quantum theory; that it was the "only completely coherent approach to explaining both the contents of quantum mechanics and the appearance of the world. Please help improve this article by adding citations to reliable sources. Unsourced material may be challenged and removed. January Learn how and when to remove this template message As with the other interpretations of quantum mechanics, the many-worlds interpretation is motivated by behavior that can be illustrated by the double-slit experiment. When particles of light or anything else are passed through the double slit, a calculation assuming wave-like behavior of light can be used to identify where the particles are likely to be observed. Yet when the particles are observed in this experiment, they appear as particles i. Some versions of the Copenhagen interpretation of quantum mechanics proposed a process of " collapse " in which an indeterminate quantum system would probabilistically collapse down onto, or select, just one determinate outcome to "explain" this phenomenon of observation. Wavefunction collapse was widely regarded as artificial and ad hoc [citation needed], so an alternative interpretation in which the behavior of measurement could be understood from more fundamental physical principles was considered desirable. Everett stated that for a composite system â€” for example a subject the "observer" or measuring apparatus observing an object the "observed" system, such as a particle â€” the statement that either the observer or the observed has a well-defined state is meaningless; in modern parlance, the observer and the observed have become entangled ; we can only specify the state of one relative to the other, i. This led Everett to derive from the unitary, deterministic dynamics alone i. Everett noticed that the unitary, deterministic dynamics alone decreed that after an observation is made each element of the quantum superposition of the combined subjectâ€"object wavefunction contains two "relative states": The subsequent evolution of each pair of relative subjectâ€"object states proceeds with complete indifference as to the presence or absence of the other elements, as if wavefunction collapse has occurred, which has the consequence that later observations are always consistent with the earlier observations. All that one does, really, is to calculate conditional probabilitiesâ€"in other words, the probability of A happening, given B. Some people overlay it with a lot of mysticism about the wave function splitting into different parts. Reality is not a quality you can test with litmus paper. Quantum theory does this very successfully. The second issue with Bohmian mechanics may at first sight appear rather harmless, but which on a closer look develops considerable destructive power: These are the components of the post-measurement state that do not guide any particles because they do not have the actual configuration q in their support. At first sight, the empty branches do not appear problematic but on the contrary very helpful as they enable the theory to explain unique outcomes of measurements. On a closer view, though, one must admit that these empty branches do not actually disappear. Now, if the Everettian theory may be accused of ontological extravagance, then Bohmian mechanics could be accused of ontological wastefulness. On top of the ontology of empty branches comes the additional ontology of particle positions that are, on account of the quantum equilibrium hypothesis, forever unknown to the observer. Yet, the actual configuration is never needed for the calculation of the statistical predictions in experimental reality, for these can be obtained by mere wavefunction algebra. From this perspective, Bohmian mechanics may appear as a wasteful and redundant theory. I think it is considerations like these that are the biggest obstacle in the way of a general acceptance of Bohmian mechanics. There is no consensus on whether this has been successful. Everett stopped doing research in theoretical physics shortly after obtaining his Ph. Decision theory[edit] A decision-theoretic derivation of the Born rule from Everettarian assumptions, was produced by David Deutsch [40] and refined by Wallace â€" [41] [42] [43] [44] and Saunders He has proved that the Born rule and the collapse of the wave function follow from a game-theoretical strategy, namely the Nash equilibrium within a von Neumann zero-sum game between nature and observer. Carroll , building on work by Lev Vaidman , [55] proposed a similar approach based on self-locating uncertainty. This section does not cite any sources. Please help improve this section by adding citations to reliable sources. Measurement is regarded as causing M and S to interact. After S interacts with M, it is no longer possible to describe either system by an independent state. According to Everett, the only meaningful descriptions of each system are relative states: Schematic illustration of splitting as a result of a repeated measurement. For example, consider the smallest possible truly quantum system S, as shown in the illustration. This describes for instance, the spin-state of an electron. Considering a specific axis say the z-axis the north pole represents spin "up" and the south pole, spin "down". The superposition states of the system are described by the surface of a sphere called the Bloch sphere. To perform a measurement on S, it is made to interact with another similar system M. After the interaction, the combined system is described by a state that ranges over a six-dimensional space the reason for the number six is explained in the article on the Bloch sphere. This six-dimensional object can also be regarded as a quantum superposition of two "alternative histories" of the original system S, one in which "up" was observed and the other in which "down" was observed. Each subsequent binary measurement that is interaction with a system M causes a similar split in the history tree. The accepted terminology is somewhat misleading because it is incorrect to regard the universe as splitting at certain times; at any given instant there is one state in one universe. January Learn how and when to remove this template message In his doctoral dissertation, Everett proposed that rather than modeling an isolated quantum system subject to external observation, one could mathematically model an object as well as its observers as purely physical systems within the mathematical framework developed by Paul Dirac , von Neumann and others, discarding altogether the ad hoc mechanism of wave function collapse. One such is the relative state formulation. It makes two assumptions: Secondly, observation or measurement has no special laws or mechanics, unlike in the Copenhagen interpretation which considers the wavefunction collapse as a special kind of event which occurs as a result of observation. Instead, measurement in the relative state formulation is the consequence of a configuration change in the memory of an observer described by the same basic wave physics as the object being modeled. These splits generate a possible tree as shown in the graphic below. Subsequently, DeWitt introduced the term "world" to describe a complete measurement history of an observer, which corresponds roughly to a single branch of that tree. Note that "splitting" in this sense is hardly new or even quantum mechanical. The idea of a space of complete alternative histories had already been used in the theory of probability since the mids for instance to model Brownian motion. Partial trace as relative state. Light blue rectangle on upper left denotes system in pure state. Trellis shaded rectangle in upper right denotes a possibly mixed state. Mixed state from observation is partial trace of a linear superposition of states as shown in lower right-hand corner. An observation or measurement is modeled by applying the wave equation to the entire system comprising the observer and the object. Since many observation-like events have happened and are constantly happening, there are an enormous and growing number of simultaneously existing states. Each product of subsystem states in the overall superposition evolves over time independently of other products. Once the subsystems interact, their states have become correlated or entangled and it is no longer possible to consider them independent of one another. Properties of the theory[edit] MWI removes the observer-dependent role in the quantum measurement process by replacing wavefunction collapse with quantum decoherence. Quantum cosmology also becomes intelligible, since there is no need anymore for an observer outside of the universe. MWI achieves this by removing wavefunction collapse , which is indeterministic and non-local, from the deterministic and local equations of quantum theory. Comparative properties and possible experimental tests[edit] One of the salient properties of the many-worlds interpretation is that it does not require an exceptional method of wave function collapse to explain it. In most no-collapse interpretations, the evolution of the quantum state of the Universe is the same. Still, one might imagine that there is an experiment distinguishing the MWI from another no-collapse interpretation based on the difference in the correspondence between the formalism and the experience the results of experiments. Since then Lockwood , Vaidman and others have made similar proposals. Many other controversial ideas have been put forward though, such as a recent claim that cosmological observations could test the theory, [63] and another claim by Rainer Plaga , published in Foundations of Physics , that communication might be possible between worlds. January Learn how and when to remove this template message In the Copenhagen interpretation , the mathematics of quantum mechanics allows one to predict probabilities for the occurrence of various events. When an event occurs, it becomes part of the definite reality, and alternative possibilities do not. There is no necessity to say anything definite about what is not observed. The universe decaying to a new vacuum state[edit] Any event that changes the number of observers in the universe may have experimental consequences. This has not happened and is cited as evidence in favor of many-worlds. In some worlds, quantum tunnelling to a true vacuum state has happened but most other worlds escape this tunneling and remain viable. This can be thought of as a variation on quantum suicide. This objection is saying that it is not clear what is precisely meant by branching, and point to the lack of self-contained criteria specifying branching. In Dirac notation a measurement is complete when:

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7: Everett's Relative-State Formulation of Quantum Mechanics (Stanford Encyclopedia of Philosophy)

Dieter Zeh --Quantum Darwinism and envariance / Wojciech H. Zurek --Using qubits to learn about "it" / Juan Pablo Paz --Quantum gravity as an ordinary gauge theory / Juan M. Maldacena --The Everett interpretation of quantum mechanics / Bryce S. DeWitt --Part IV.

Quantum logic In the mathematically rigorous formulation of quantum mechanics developed by Paul Dirac , [25] David Hilbert , [26] John von Neumann , [27] and Hermann Weyl , [28] the possible states of a quantum mechanical system are symbolized [29] as unit vectors called state vectors. Formally, these reside in a complex separable Hilbert space â€”variously called the state space or the associated Hilbert space of the systemâ€”that is well defined up to a complex number of norm 1 the phase factor. In other words, the possible states are points in the projective space of a Hilbert space, usually called the complex projective space. The exact nature of this Hilbert space is dependent on the systemâ€—for example, the state space for position and momentum states is the space of square-integrable functions, while the state space for the spin of a single proton is just the product of two complex planes. Each observable is represented by a maximally Hermitian precisely: Each eigenstate of an observable corresponds to an eigenvector of the operator, and the associated eigenvalue corresponds to the value of the observable in that eigenstate. In the formalism of quantum mechanics, the state of a system at a given time is described by a complex wave function , also referred to as state vector in a complex vector space. For example, it allows one to compute the probability of finding an electron in a particular region around the nucleus at a particular time. Contrary to classical mechanics, one can never make simultaneous predictions of conjugate variables , such as position and momentum, to arbitrary precision. For instance, electrons may be considered to a certain probability to be located somewhere within a given region of space, but with their exact positions unknown. Contours of constant probability density, often referred to as "clouds", may be drawn around the nucleus of an atom to conceptualize where the electron might be located with the most probability. The possible results of a measurement are the eigenvalues of the operator representing the observableâ€”which explains the choice of Hermitian operators, for which all the eigenvalues are real. The probability distribution of an observable in a given state can be found by computing the spectral decomposition of the corresponding operator. The probabilistic nature of quantum mechanics thus stems from the act of measurement. This is one of the most difficult aspects of quantum systems to understand. It was the central topic in the famous Bohrâ€—Einstein debates , in which the two scientists attempted to clarify these fundamental principles by way of thought experiments. In the decades after the formulation of quantum mechanics, the question of what constitutes a "measurement" has been extensively studied. Newer interpretations of quantum mechanics have been formulated that do away with the concept of " wave function collapse " see, for example, the relative state interpretation. The basic idea is that when a quantum system interacts with a measuring apparatus, their respective wave functions become entangled , so that the original quantum system ceases to exist as an independent entity. For details, see the article on measurement in quantum mechanics. Instead, it makes a prediction using a probability distribution ; that is, it describes the probability of obtaining the possible outcomes from measuring an observable. Often these results are skewed by many causes, such as dense probability clouds. Probability clouds are approximate but better than the Bohr model whereby electron location is given by a probability function , the wave function eigenvalue , such that the probability is the squared modulus of the complex amplitude , or quantum state nuclear attraction. Hence, uncertainty is involved in the value. There are, however, certain states that are associated with a definite value of a particular observable. These are known as eigenstates of the observable "eigen" can be translated from German as meaning "inherent" or "characteristic". Everything appears to have a definite position, a definite momentum, a definite energy, and a definite time of occurrence. Rather, it provides only a range of probabilities in which that particle might be given its momentum and momentum probability. Therefore, it is helpful to use different words to describe states having uncertain values and states having definite values eigenstates. Usually, a system will not be in an eigenstate of the observable particle we are interested in. However, if one measures the observable, the wave function will instantaneously be an eigenstate or "generalized" eigenstate of that observable. This process is known as wave function collapse , a controversial and much-debated process [36] that involves expanding the system under study to include the measurement device. If one knows the corresponding wave function at the instant before the measurement, one will be able to compute the probability of the wave function collapsing into each of the possible eigenstates. For example, the free particle in the previous example will usually have a wave function that is a wave packet centered around some mean position x0 neither an eigenstate of position nor of momentum. When one measures the position of the particle, it is impossible to predict with certainty the result. After the measurement is performed, having obtained some result x, the wave function collapses into a position eigenstate centered at x. The time evolution of wave functions is deterministic in the sense thatâ€”given a wave function at an initial timeâ€"it makes a definite prediction of what the wave function will be at any later time. A time-evolution simulation can be seen here. However, the wave packet will also spread out as time progresses, which means that the position becomes more uncertain with time. This also has the effect of turning a position eigenstate which can be thought of as an infinitely sharp wave packet into a broadened wave packet that no longer represents a definite, certain position eigenstate. Probability densities corresponding to the wave functions of an electron in a hydrogen atom possessing definite energy levels increasing from the top of the image to the bottom: Denser areas correspond to higher probability density in a position measurement. The angular momentum and energy are quantized , and take only discrete values like those shown as is the case for resonant frequencies in acoustics Some wave functions produce probability distributions that are constant, or independent of timeâ€"such as when in a stationary state of constant energy, time vanishes in the absolute square of the wave function. Many systems that are treated dynamically in classical mechanics are described by such "static" wave functions. For example, a single electron in an unexcited atom is pictured classically as a particle moving in a circular trajectory around the atomic nucleus , whereas in quantum mechanics it is described by a static, spherically symmetric wave function surrounding the nucleus Fig. Whereas the absolute value of the probability amplitude encodes information about probabilities, its phase encodes information about the interference between quantum states. This gives rise to the "wave-like" behavior of quantum states. Even the helium atomâ€"which contains just one more electron than does the hydrogen atomâ€"has defied all attempts at a fully analytic treatment. There exist several techniques for generating approximate solutions, however. In the important method known as perturbation theory , one uses the analytic result for a simple quantum mechanical model to generate a result for a more complicated model that is related to the simpler model by for one example the addition of a weak potential energy. Another method is the "semi-classical equation of motion" approach, which applies to systems for which quantum mechanics produces only weak small deviations from classical behavior. These deviations can then be computed based on the classical motion. This approach is particularly important in the field of quantum chaos. Mathematically equivalent formulations of quantum mechanics[edit] There are numerous mathematically equivalent formulations of quantum mechanics. One of the oldest and most commonly used formulations is the " transformation theory " proposed by Paul Dirac.

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The many-worlds interpretation is an interpretation of quantum mechanics that asserts the objective reality of the universal wavefunction and denies the actuality of wavefunction collapse.

The many-worlds interpretation shares many similarities with later, other "post-Everett" interpretations of quantum mechanics which also use decoherence to explain the process of measurement or wavefunction collapse. MWI treats the other histories or worlds as real since it regards the universal wavefunction as the "basic physical entity" [18] or "the fundamental entity, obeying at all times a deterministic wave equation". MWI is distinguished by two qualities: Copenhagenism or mental postulates such as the many-minds interpretation makes. Many worlds is often referred to as a theory , rather than just an interpretation, by those who propose that many worlds can make testable predictions such as David Deutsch or is falsifiable such as Everett or that all the other, non-MWI, are inconsistent, illogical or unscientific in their handling of measurements; Hugh Everett argued that his formulation was a metatheory , since it made statements about other interpretations of quantum theory; that it was the "only completely coherent approach to explaining both the contents of quantum mechanics and the appearance of the world" [20]. When particles of light or anything else are passed through the double slit, a calculation assuming wave-like behavior of light is needed to identify where the particles are likely to be observed. Yet when the particles are observed in this experiment, they appear as particles i. The Copenhagen interpretation of quantum mechanics proposed a process of " collapse " in which an indeterminate quantum system would probabilistically collapse down onto, or select, just one determinate outcome to "explain" this phenomenon of observation. Wavefunction collapse was widely regarded as artificial and ad-hoc, so an alternative interpretation in which the behavior of measurement could be understood from more fundamental physical principles was considered desirable. Everett noted that for a composite system for example that formed by a particle interacting with a measuring apparatus, or more generally by a subject the "observer" observing an object the "observed" system the statement that a subsystem i. This led Everett to derive from the unitary, deterministic dynamics alone i. Everett noticed that the unitary, deterministic dynamics alone decreed that after an observation is made each element of the quantum superposition of the combined subject-object wavefunction contains two relative states: The subsequent evolution of each pair of relative subject-object states proceeds with complete indifference as to the presence or absence of the other elements, as if wavefunction collapse has occurred, which has the consequence that later observations are always consistent with the earlier observations. Since Everett stopped doing research in theoretical physics shortly after obtaining his Ph. Quantum cosmology also becomes intelligible, since there is no need anymore for an observer outside of the universe. MWI allows quantum mechanics to become a realist , deterministic , local theory making it more akin to classical physics including the theory of relativity , at the expense of losing counterfactual definiteness. The simplest way to see that the many-worlds metatheory is a local theory is to note that it requires that the wavefunction obey some relativistic wave equation, the exact form of which is currently unknown, but which is presumed to be locally Lorentz invariant at all times and everywhere. This is equivalent to imposing the requirement that locality is enforced at all times and everywhere. Therefore many-worlds is a local theory. Another way of seeing this is to examine how macrostates evolve. Macrostates descriptions of objects evolve in a local fashion. Worlds split as the macrostate description divides inside the light cone of the triggering event. Thus the splitting is a local process, transmitted causally at light or sub-light speeds. This is the main objection opponents of this interpretation raise,[citation needed] saying that it is not clear what is precisely meant by branching, and point to lack of self contained criterion specifying branching to be described. In Dirac notation a measurement is complete when: Before the measurement has started the observer states are identical; after the measurement is complete the observer states are orthonormal. Thus branching is complete when the measurement is complete. Since the role of the observer and measurement per se plays no special role in MWI measurements are handled as all other interactions are there is no need for a precise definition of what an observer or a measurement is -- just as in Newtonian physics no precise definition of either an observer or a measurement was required or expected. In all circumstances the universal wavefunction is still available to give a complete description of reality. Also, it is a common misconception to think that branches are completely separate. But the existence of a preferred basis can only be established by the process of decoherence, which is itself probabilistic. We cannot be sure that the universe is a quantum multiverse until we have a theory of everything and, in particular, a successful theory of quantum gravity. Whilst quantum gravity or string theory may be non-linear in this respect there is no evidence to indicate this at the moment. Conservation of energy is grossly violated if every instant infinite amounts of new matter are generated. Conservation of energy is not violated since the energy of each branch has to be weighted by its probability, according to the standard formula for the conservation of energy in quantum theory. This results in the total energy of the multiverse being conserved. MWI is a simpler theory since it has fewer postulates. If a state is a superposition of two states Psi A and Psi B , i. This seems to throw away the information in the probability amplitudes. Such a theory makes little sense. The magnitude of the coefficients provides the weighting that makes the branches or universes "unequal", as Everett and others have shown, leading the emergence of the conventional probabilistic rules. MWI splitting is instant and total: This leads to a hopeless muddle with everyone splitting differently. Measurement is regarded as causing M and S to interact. After S interacts with M, it is no longer possible to describe either system by an independent state. According to Everett, the only meaningful descriptions of each system are relative states: Schematic representation of pair of "smallest possible" quantum mechanical systems prior to interaction: Measured system S and measurement apparatus M. Systems such as S are referred to as 1- qubit systems. For example, consider the smallest possible truly quantum system S, as shown in the illustration. This describes for instance, the spin-state of an electron. Considering a specific axis say the z-axis the north pole represents spin "up" and the south pole, spin "down". The superposition states of the system are described by the surface of a sphere called the Bloch sphere. To perform a measurement on S, it is made to interact with another similar system M. After the interaction, the combined system is described by a state that ranges over a six-dimensional space the reason for the number six is explained in the article on the Bloch sphere. This six-dimensional object can also be regarded as a quantum superposition of two "alternative histories" of the original system S, one in which "up" was observed and the other in which "down" was observed. Each subsequent binary measurement that is interaction with a system M causes a similar split in the history tree. The accepted terminology is somewhat misleading because it is incorrect to regard the universe as splitting at certain times; at any given instant there is one state in one universe. Schematic illustration of splitting as a result of a repeated measurement. One such idea is discussed in the next section. The relative-state interpretation makes two assumptions. The second is that observation or measurement has no special role, unlike in the Copenhagen interpretation which considers the wavefunction collapse as a special kind of event which occurs as a result of observation. These splits generate a possible tree as shown in the graphic below. Subsequently DeWitt introduced the term "world" to describe a complete measurement history of an observer, which corresponds roughly to a single branch of that tree. Note that "splitting" in this sense, is hardly new or even quantum mechanical. The idea of a space of complete alternative histories had already been used in the theory of probability since the mid s for instance to model Brownian motion. Partial trace as relative state. Light blue rectangle on upper left denotes system in pure state. Trellis shaded rectangle in upper right denotes a possibly mixed state. Mixed state from observation is partial trace of a linear superposition of states as shown in lower left-hand corner. An observation or measurement of an object by an observer is modeled by applying the wave equation to the entire system comprising the observer and the object. Since many observation-like events have happened, and are constantly happening, there are an enormous and growing number of simultaneously existing states. Once the subsystems interact, their states are no longer independent. Each product of subsystem states in the overall superposition evolves over time independently of other products. The subsystems states have become correlated or entangled and it is no longer possible to consider them independent of one another. Successive measurements with successive splittings [edit] Comparative properties and experimental support One of the salient properties of the many-worlds interpretation is that observation does not require an exceptional construct such as wave function collapse to explain it. Many physicists, however, dislike the implication that there are infinitely many non-observable alternate universes. There may be cosmological, observational evidence. In the many-worlds interpretation, all these events occur simultaneously. What meaning should be given to these probability calculations? And why do we observe, in our history, that the events with a higher computed probability seem to have occurred more often? One answer to these questions is to say that there is a probability measure on the space of all possible universes, where a possible universe is a complete path in the tree of branching universes. This is indeed what the calculations give. Then we should expect to find ourselves in a universe with a relatively high probability rather than a relatively low probability: As an interpretation which like other interpretations is consistent with the equations, it is hard to find testable predictions of MWI. By repeating this process a number of times, their continued consciousness would be arbitrarily unlikely unless MWI was true, when they would be alive in all the worlds where the random decay was on their side. From their viewpoint they would be immune to this death process. Clearly, if MWI does not hold, they would be dead in the one world. Other people would generally just see them die and would not be able to benefit from the result of this experiment. There is also the claim that the universe should have already experienced quantum tunnelling to a true vacuum state. This has not happened. That may increase the probability that many-worlds is true. All the possible consistent states of the measured system and the measuring apparatus including the observer are present in a physically real quantum superposition , not just formally mathematical superposition, as in other interpretations. Such a superposition of consistent state combinations of different systems is called an entangled state. It can rather be derived from the other axioms of quantum mechanics. All that has to be assumed is that if the state is an eigenstate of the observable A, then the result a of the measurement is certain. This means that a second axiom of quantum mechanics can be removed. In other interpretations it is not comprehensible why the absolute square is used and not some other arbitrary, more complicated expression of the eigenvalue component say, the square root or some polynomial of its norm. One might argue that postulating the existence of many worlds is some kind of axiomatic assumption, but each world is merely an element in the quantum superposition of the universal wavefunction ; quantum superpositions are a common and indispensable part of all interpretations of quantum theory , as is most clearly illustrated in the path integral formulation of quantum mechanics.

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9: Quantum mechanics - Wikipedia

Quantum theory represents a unifying theme within the book, along with topics such as the nature of physical reality, the arrow of time, models of the universe, superstrings, gravitational radiation, quantum gravity and cosmic inflation.

In this interpretation, every event is a branch point; the cat is both alive and dead, even before the box is opened, but the "alive" and "dead" cats are in different branches of the universe, both of which are equally real, but which do not interact with each other. Many-worlds implies that all possible alternate histories and futures are real, each representing an actual "world" or "universe". The theory is also referred to as MWI, the relative state formulation, the Everett interpretation, the theory of the universal wavefunction, many-universes interpretation, multiverse theory or just many-worlds. The original relative state formulation is due to Hugh Everett in MWI is one of many multiverse hypotheses in physics and philosophy. It is currently considered a mainstream interpretation along with the other decoherence interpretations, collapse theories including the historical Copenhagen interpretation ,[11] and hidden variable theories such as the Bohmian mechanics. Before many-worlds, reality had always been viewed as a single unfolding history. Many-worlds, however, views historical reality as a many-branched tree, wherein every possible quantum outcome is realised. He went on to assert that what the equation that won him a Nobel prize seems to be describing is several different histories, they are "not alternatives but all really happen simultaneously". This is the earliest known reference to the many-worlds. The many-worlds interpretation shares many similarities with later, other "post-Everett" interpretations of quantum mechanics which also use decoherence to explain the process of measurement or wavefunction collapse. MWI treats the other histories or worlds as real since it regards the universal wavefunction as the "basic physical entity"[20] or "the fundamental entity, obeying at all times a deterministic wave equation". MWI is distinguished by two qualities: Decoherent interpretations of many-worlds using einselection to explain how a small number of classical pointer states can emerge from the enormous Hilbert space of superpositions have been proposed by Wojciech H. Other states decohere into mixtures of stable pointer states that can persist, and, in this sense, exist: Many-worlds is often referred to as a theory , rather than just an interpretation, by those who propose that many-worlds can make testable predictions such as David Deutsch or is falsifiable such as Everett or by those who propose that all the other, non-MW interpretations, are inconsistent, illogical or unscientific in their handling of measurements; Hugh Everett argued that his formulation was a metatheory , since it made statements about other interpretations of quantum theory; that it was the "only completely coherent approach to explaining both the contents of quantum mechanics and the appearance of the world. When particles of light or anything else are passed through the double slit, a calculation assuming wave-like behavior of light can be used to identify where the particles are likely to be observed. Yet when the particles are observed in this experiment, they appear as particles i. Some versions of the Copenhagen interpretation of quantum mechanics proposed a process of " collapse " in which an indeterminate quantum system would probabilistically collapse down onto, or select, just one determinate outcome to "explain" this phenomenon of observation. Wavefunction collapse was widely regarded as artificial and ad hoc , so an alternative interpretation in which the behavior of measurement could be understood from more fundamental physical principles was considered desirable. Everett stated that for a composite system â€” for example a subject the "observer" or measuring apparatus observing an object the "observed" system, such as a particle â€” the statement that either the observer or the observed has a well-defined state is meaningless; in modern parlance, the observer and the observed have become entangled ; we can only specify the state of one relative to the other, i. This led Everett to derive from the unitary, deterministic dynamics alone i. Everett noticed that the unitary, deterministic dynamics alone decreed that after an observation is made each element of the quantum superposition of the combined subjectâ€"object wavefunction contains two "relative states": The subsequent evolution of each pair of relative subjectâ€"object states proceeds with complete indifference as to the presence or absence of the other elements, as if wavefunction collapse has occurred, which has the consequence that later observations are always consistent with the earlier observations. All that one does, really, is to calculate conditional probabilitiesâ€"in other words, the probability of A happening, given B. Some people overlay it with a lot of mysticism about the wave function splitting into different parts. Reality is not a quality you can test with litmus paper. Quantum theory does this very successfully. The second issue with Bohmian mechanics may at first sight appear rather harmless, but which on a closer look develops considerable destructive power: These are the components of the post-measurement state that do not guide any particles because they do not have the actual configuration q in their support. At first sight, the empty branches do not appear problematic but on the contrary very helpful as they enable the theory to explain unique outcomes of measurements. On a closer view, though, one must admit that these empty branches do not actually disappear. Now, if the Everettian theory may be accused of ontological extravagance, then Bohmian mechanics could be accused of ontological wastefulness. On top of the ontology of empty branches comes the additional ontology of particle positions that are, on account of the quantum equilibrium hypothesis, forever unknown to the observer. Yet, the actual configuration is never needed for the calculation of the statistical predictions in experimental reality, for these can be obtained by mere wavefunction algebra. From this perspective, Bohmian mechanics may appear as a wasteful and redundant theory. I think it is considerations like these that are the biggest obstacle in the way of a general acceptance of Bohmian mechanics. There is no consensus on whether this has been successful. Everett stopped doing research in theoretical physics shortly after obtaining his Ph. Decision theory A decision-theoretic derivation of the Born rule from Everettarian assumptions, was produced by David Deutsch [40] and refined by Wallace â€" [41][42][43][44] and Saunders He has proved that the Born rule and the collapse of the wave function follow from a game-theoretical strategy, namely the Nash equilibrium within a von Neumann zero-sum game between nature and observer. Carroll , building on work by Lev Vaidman ,[55] proposed a similar approach based on self-locating uncertainty. Measurement is regarded as causing M and S to interact. After S interacts with M, it is no longer possible to describe either system by an independent state. According to Everett, the only meaningful descriptions of each system are relative states: Schematic illustration of splitting as a result of a repeated measurement. For example, consider the smallest possible truly quantum system S, as shown in the illustration. This describes for instance, the spin-state of an electron. Considering a specific axis say the z-axis the north pole represents spin "up" and the south pole, spin "down". The superposition states of the system are described by the surface of a sphere called the Bloch sphere. To perform a measurement on S, it is made to interact with another similar system M. After the interaction, the combined system is described by a state that ranges over a six-dimensional space the reason for the number six is explained in the article on the Bloch sphere. This six-dimensional object can also be regarded as a quantum superposition of two "alternative histories" of the original system S, one in which "up" was observed and the other in which "down" was observed. Each subsequent binary measurement that is interaction with a system M causes a similar split in the history tree. The accepted terminology is somewhat misleading because it is incorrect to regard the universe as splitting at certain times; at any given instant there is one state in one universe. Relative state In his doctoral dissertation, Everett proposed that rather than modeling an isolated quantum system subject to external observation, one could mathematically model an object as well as its observers as purely physical systems within the mathematical framework developed by Paul Dirac , von Neumann and others, discarding altogether the ad hoc mechanism of wave function collapse. One such is the relative state formulation. It makes two assumptions: Secondly, observation or measurement has no special laws or mechanics, unlike in the Copenhagen interpretation which considers the wavefunction collapse as a special kind of event which occurs as a result of observation. Instead, measurement in the relative state formulation is the consequence of a configuration change in the memory of an observer described by the same basic wave physics as the object being modeled. These splits generate a possible tree as shown in the graphic below. Subsequently, DeWitt introduced the term "world" to describe a complete measurement history of an observer, which corresponds roughly to a single branch of that tree. Note that "splitting" in this sense is hardly new or even quantum mechanical. The idea of a space of complete alternative histories had already been used in the theory of probability since the mids for instance to model Brownian motion. Partial trace as relative state. Light blue rectangle on upper left denotes system in pure state. Trellis shaded rectangle in upper right denotes a possibly mixed state. Mixed state from observation is partial trace of a linear superposition of states as shown in lower right-hand corner. An observation or measurement is modeled by applying the wave equation to the entire system comprising the observer and the object. Since many observation-like events have happened and are constantly happening, there are an enormous and growing number of simultaneously existing states. Each product of subsystem states in the overall superposition evolves over time independently of other products. Once the subsystems interact, their states have become correlated or entangled and it is no longer possible to consider them independent of one another. Properties of the theory MWI removes the observer-dependent role in the quantum measurement process by replacing wavefunction collapse with quantum decoherence. Quantum cosmology also becomes intelligible, since there is no need anymore for an observer outside of the universe. MWI is a realist , deterministic , arguably local theory, akin to classical physics including the theory of relativity , at the expense of losing counterfactual definiteness. MWI achieves this by removing wavefunction collapse , which is indeterministic and non-local, from the deterministic and local equations of quantum theory. Comparative properties and possible experimental tests One of the salient properties of the many-worlds interpretation is that it does not require an exceptional method of wave function collapse to explain it. In most no-collapse interpretations, the evolution of the quantum state of the Universe is the same. Still, one might imagine that there is an experiment distinguishing the MWI from another no-collapse interpretation based on the difference in the correspondence between the formalism and the experience the results of experiments. Since then Lockwood , Vaidman and others have made similar proposals. Many other controversial ideas have been put forward though, such as a recent claim that cosmological observations could test the theory,[63] and another claim by Rainer Plaga , published in Foundations of Physics , that communication might be possible between worlds. When an event occurs, it becomes part of the definite reality, and alternative possibilities do not. There is no necessity to say anything definite about what is not observed. The universe decaying to a new vacuum state Any event that changes the number of observers in the universe may have experimental consequences. Some cosmologists argue that the universe is in a false vacuum state and that consequently the universe should have already experienced quantum tunnelling to a true vacuum state. This has not happened and is cited as evidence in favor of many-worlds. In some worlds, quantum tunnelling to a true vacuum state has happened but most other worlds escape this tunneling and remain viable. This can be thought of as a variation on quantum suicide. This objection is saying that it is not clear what is precisely meant by branching, and point to the lack of self-contained criteria specifying branching. In Dirac notation a measurement is complete when:

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