Interpretation of Quantum Mechanics. A view of our universe

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Abstract.
The interpretation of quantum mechanics has been disputed ever since the advent of the theory in the 1920's. Famous are the discussions over long time between Einstein and Bohr. Einstein refused to accept the so-called Copenhagen interpretation, where the wave function collapses at a measurement and where the outcome of the measurement is essentially accidental ("God does not play dice"). Alternative interpretations have appeared, but the Copenhagen school has dominated the thoughts throughout the decades. One interesting interpretation was formulated in 1957 by Hugh Everett at Princeton, a student of John Wheeler, which abandons the wave-function collapse. In this model the universe is governed entirely by the Schrödinger equation, which does not allow for any collapse. In Everett's model after a measurement the wave function is separated into different branches that do not interact. This model was left unnoticed for long time until Bryce DeWitt took it up in 1970 and termed it "Many-Worlds Interpretation", a term that in some sense is misleading. Everett's model is incomplete, and it was later supplemented by the theory of decoherence, which explains how the different branches decouple as a result of the interaction with the environment. This extended model has in recent years gained increased respect, and some believe that it is the only model made available so far that is fully consistent with quantum mechanics. This interpretation can also shed some light on the development of the universe and, in particular, on the so-called Anthropic principle, which puts human beings at the center of the development.

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INTRODUCTION

When quantum mechanics was introduced into physics it meant a new way of thinking that was to a large extent counterintuitive, and its interpretation was from the start—and still is—disputed among the scholars. Most famous is the long dispute between Niels Bohr and Albert Einstein that lasted for several decades (Fig. 1). Bohr was the leader or coordinator of the so-called Copenhagen school, and he surrounded himself for extended periods of time at the newly erected Bohr Institute in Copenhagen with a number of bright young scientists, Werner Heisenberg, Wolfgang Pauli and others (Fig. 2).

THE COPENHAGEN INTERPRETATION

The most controversial part of the so-called Copenhagen interpretation (CI) concerns the measuring process. The wave function or Schrödinger function of a state of a system

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FIGURE 1. The long dispute about the interpretation of quantum mechanics between Albert Einstein and Niels Bohr is classical.

FIGURE 2. Niels Bohr (left) discusses the foundation of quantum mechanics at the Bohr Institute with Werner Heisenberg (middle) and Wolfgang Pauli (right).

can generally be expressed as a superposition of eigenstates of a of particular observable

$$\Psi = \sum c_i \Phi_i \tag{1}$$

where

$$\mathscr{O}\Phi_i = E_i \Phi_i \tag{2}$$

and $\mathscr{O}$ is the operator corresponding to the observable in question and E_i is the eigenvalue of the eigenstate Φ_i.

According to the Copenhagen School—which has been the prevailing interpretation of QM for more than half a century—a measurement is a registration by a macroscopic observer, outside the system under study (Fig. 3). When an observable corresponding to the operator $\mathscr{O}$ is measured, the result can be any of the eigenvalues E_i in Eq. (1). Which value that is obtained in a particular measurement cannot be predicted—only the probability for the various results in a long series of identical measurements. The latter is based upon the *Born statistical interpretation*, according to which the probability for

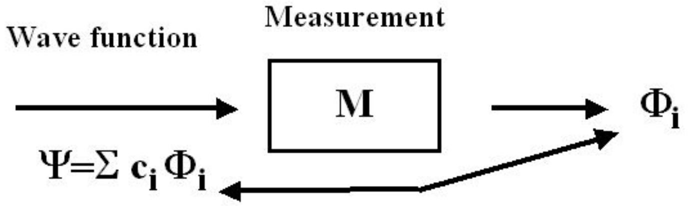


FIGURE 3. According to the Copenhagen interpretation, when an observable is being measured, the wave function of the system "collapses" into one of the eigenstates of the observable.

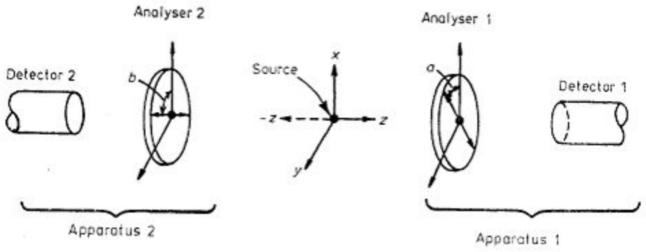


FIGURE 4. Schematic view of the famous Einsten-Podolsky-Rosen thought experiment, the purpose of which was to demonstrate that the standard (Copenhagen) interpretation of QM was impossible.

a particular result of a measurement is the square of the expansion coefficient in Eq. (1), $|c_i|^2$.

Einstein could never accept that the result of a measurement was largely accidental—"*God does not play dice*" is his famous quotation. In order to try to convince the world that the quantum mechanics according to the CI was incorrect or at least incomplete, he constructed in 1935 together with two colleagues the famous Einstein-Podolsky-Rosen thought experiment [1] (Fig. 4). Here, an atomic state is decaying by two-photon decay, where the initial as well as the final states are without angular momentum ($J = 0$). Then the photons cannot carry away any angular momentum, and the two photons must have opposite polarization orientations, but we do not know in advance what these orientations are. When one of the photons is detected and its polarization determined, we know by certainty the orientation of the other. This is the case even if the detectors are far apart (and there is no external disturbance). One possible explanation of this might be that the polarization orientations are determined at the moment of emission, although we do not know about them—a phenomenon known as "hidden variables". It was shown by John Bell [2, 3] in 1964 that the hidden-variable and the quantum-mechanical models do in fact lead to different results, when the coincidence rate of the photons is measured as function of the relative angle between the polarization filters. During the last decades very accurate and sophisticated experiments of EPR type were set up, and it has been verified beyond doubt that the results are in accordance with the quantum-mechanical interpretation— the hidden-variable hypothesis could definitely be ruled out [4, 5, 6, 7].

Another thought experiment was the famous "Schrödinger's cat" (Fig. 5). Here, a cat

FIGURE 5. The "Schrödinger's cat" can according to the CI be in a superposition of dead and alive states before an inspection is made.

is contained in a closed box together with a deadly poison that can be injected into the cat when a radioactive atom is decaying. Before opening the lid of the box, we do not know if the poison is injected or not, and then—according to the CI, treating the cat as a quantum-mechanical system—the cat is in a superposition of a dead and an alive state. This is absurd, of course, and the example was constructed by Schrödinger to demonstrate the incompleteness of the QM interpretation. The standard reply to this dilemma is that QM cannot be applied to macroscopic objects like living creatures. Then the obvious question is where the borderline is between micro- and macroscopic objects.

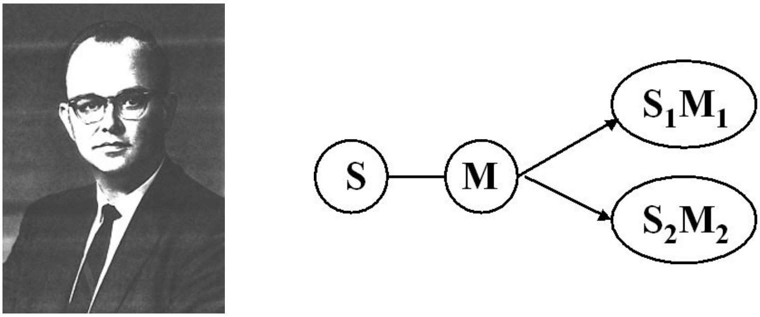
Problems with the Copenhagen interpretation

The Copenhagen interpretation of Quantum Mechanics has some obvious shortcomings, particularly

- the measurement process requires an external macroscopic observer;
- the collapse of the wave function after a measurement does not follow any known law of physics;
- artificial border between micro and macro systems, and it is unclear how classicality emerges from the quantum world.

THE EVERETT MODEL. IMPORTANCE OF COHERENCE

In 1957, a graduate student at Princeton university, Hugh Everett, supervised by the well-known nuclear scientist John Wheeler, proposed a new interpretation of quantum mechanics, which he called "*Relative-state formulation*" [8]. The basic idea of Everett's model is that a system (S) together with the measuring device (M), both treated quantum mechanically, are supposed to exactly follow the time-dependent Schödinger equation, which among other things implies that the collapse of the wave function is abandoned (Fig. 6). Also the measuring device is modified by the measurement, and its final state depends on the result of the measurement. Before a measurement, the state of the combined system is normally in a superposition of eigenstates (entanglement) (Eq. 1), and after the measurement the various components of the wave function still exist but are



Hugh Everett

FIGURE 6. In 1957 Hugh Everett proposed a new model for the interpretation of QM, according to which the wave function is after a measurement separated into different components with no interaction with each other ("different worlds"). No collapse of the wave function.

assumed to have no contact with each other. This model was left unnoticed for more than one decade, until Bryce DeWitt took it up around 1970 and coined the term "*Multiple Worlds*" [9]. This term is, however, somewhat misleading, since the separated parts of the wave function still describe the same physical world. Sometimes the term "*Multiple Minds*" is preferred.

The Everett-DeWitt model is incomplete, since it does not explain why there is no coupling between the various components after a measurement. In the 1970’s and 80’s important modifications of the model were introduced by Dieter Zeh [10] and Wojciech H. Zurek [11]. Here, the interaction with the environment is assumed to lead to a gradual—but normally quite fast—decoherence of the components (Fig. 7), and eventually this leads to a complete decoupling. Also this process is quantum-mechanical and can be studied in detail theoretically, and it has also been observed experimentally in simple systems [12, 13]. The decoupled components correspond to states that are stable against further environmental interactions—so-called "*pointer states*"—that correspond to classical states (Fig. 8). This is known as the *"emergence of classicality"* from the quantum-mechanical picture. This process has some resemblance of the development of stable species of living organisms and is therefore also termed *"Quantum Darwinism"*.

Advantages of the Everett-DeWitt model with decoherence

The Everett-DeWitt model with decoherence has particularly the following advantages compared to the Copenhagen interpretation:

- the Schrödinger equation is strictly valid at all instances—no collapse of the wave function;
- no classical observer needed—no artificial borderline between micro and macro systems;

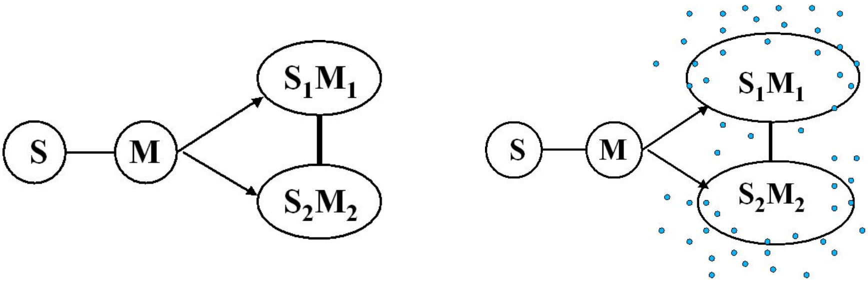


FIGURE 7. In the modification of Everett's model by Zeh, Zurek and others the components of the wave function are, immediately after the measurement coherently superposed (entangled) (left). The interaction with the environment leads to a gradual decoherence (right).

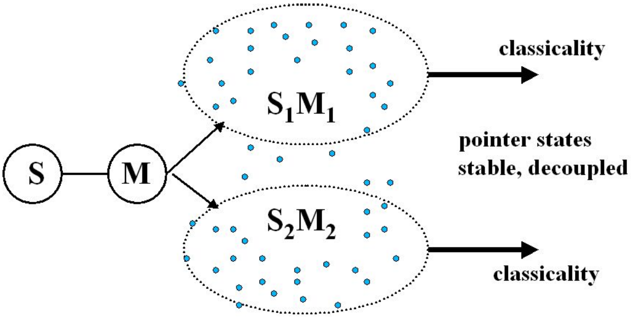


FIGURE 8. Finally, the components of the wave function, due to the interaction with the environment, have developed into stable states, which are completely decoupled from each other. This is the transition to "classicality"—also termed *"Quantum Darwinism"*.

- decoherence leads to emergency of classicality—no Schrödinger's cat.

Many scientists argue that this model represents the most consistent interpretation of quantum mechanics that has appeared so far [14]. Tegmark and Wheeler [15] state in their review article from 2001, "*100 years of Quantum Mechanics*", that

- *"...modern experiments and the discovery of decoherence have shifted the prevailing quantum interpretations away from wave function collapse towards unitary physics ...."*

Evolution of the Universe. The Anthropic Principle

One of the eternal questions is how the world can have developed in such a way that conscious, intelligent creatures have appeared, considering that at each instance things happen randomly. Then the probability for this to happen would seem to be in-

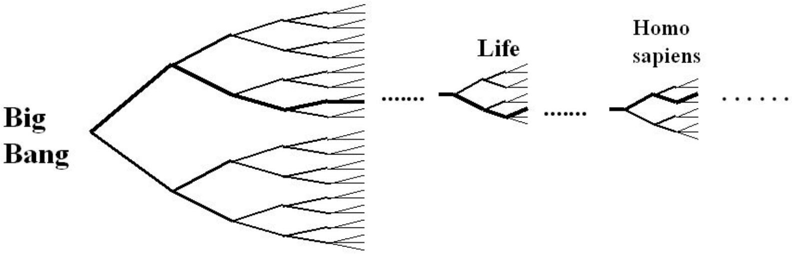


FIGURE 9. The evolution of the universe can in the Everett interpretation with decoherence be illustrated by a "bifurcation tree", which is split up in various components after each "measurement". After the decoherence process, these components are completely decoupled from each other and act—for an individual observer—as "separate worlds".

credibly small. Darwin's masterpiece, "*The Origin of Species*", is only a partial answer. One model, known as the "*Anthropic Principle*", was developed in the second half of the previous century [16, 17, 18]. There are several versions of this principle, and the "strong" principle states that the universe has to be such that conscious observers are being created at some stage. One extreme interpretation, known as Wheeler's "*Participatory Anthropic Principle*", is that a universe without conscious observers cannot exist. This is based upon the quantum-mechanical interpretation that an object will come into existence only when it is being observed—"*a tree falling in the woods without being observed does not make any noise*".

Based upon the Everett model with decoherence, we may illustrate the development of the Universe as a "bifurcation tree", starting with the Big Bang, as shown in Fig. 9. After each measurement (observation) the wave function is split into independent components. On some branch of the tree life is being evolved and later higher species and finally human beings. A conscious observer is connected to one of the numerous branches and is unaware of all the others. This implies that for such an observer the model has the same effect as the collapse of the wave function according to the Copenhagen school, although all components of the wave function do remain. Undoubtedly, such a model has some resemblance with the Anthropic Principle, and it may, in fact, shed some light on that strange principle.

There is now very strong evidence, based particularly on studies of the cosmic background radiation, that our universe did start with a Big Bang. A fundamental question is then, of course, what caused this cataclysmic event to occur, and why it did happen when it did? One hypothesis is that our universe is a "bubble" in a "super universe"—also called "*multiverse*"—due to some *vacuum fluctuation*, analogous to the corresponding process in particle physics when particle-antiparticle pairs are being created [19]. Such a process is spontaneous and has no cause. There may then be a large number of such bubbles in the multiverse, and this might make it more plausible that for some of them the conditions for life are just right.

Various possibilities of the origin and the development of our universe—from a divine

Creator to pure accidence—are discussed in the recent book by Paul Davies, *"The Goldilocks Enigma: Why is Universe just right for life"* [20].

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