MANY-WORLDS INTERPRETATION

The concept of collapse of the state vector introduced by von Neumann in 1930s and has become integral part of orthodox interpretation of quantum theory.

What evidence do we have that this collapse really takes place?

Well . . . pots and erasers now seem to be direct evidence for collapse.

What if they turn out to have a different explanation? What are the other possibilities?

As we have seen, collapse seems to be necessary to explain how a quantum system initially in linear superposition state before measurement is converted into quantum system existing in only one of measurement eigenstates after measurement process has occurred.

It was introduced into the theory because our experience is that pointers point in only one direction at a time.

Early View

The Copenhagen solution to the measurement problem is to say **there is no solution.**

Pointers point because they are part of a macroscopic measuring device which conforms to laws of classical physics.

Collapse is only way in which "**real" world** of classical objects can be related to "**unreal" world** of quantum particles.

Is it simply a useful invention, an algorithm, that allows us to predict outcomes of measurements and not a real process. Many point out that if we wish to make collapse a real physical change occurring as a real physical property of quantum system, then we must add something to theory, if only the suggestion that consciousness somehow involved. This is not a satisfactory outcome to many physicists.

So the simplest solution to problem of quantum measurement is to say there is no problem.

Over the last 60 years, quantum theory has proved its worth time and time again in the laboratory. Why change it or add extra bits to it?

Although, it is overtly a theory of the microscopic world, we know that macroscopic objects are composed of atoms and molecules, so why not accept that quantum theory applies equally well to pointers, cats and human observers? Pointers point because of collapse and that is that!!!! That is the standard view!

There is a different interpretation accepted by many. In this interpretation the observer is assumed to split into number of different, non-interacting conscious selves. Each individual self records and remembers a different result, and **all possible results are realized.**

In this interpretation, the act of measurement splits the **entire universe** into a number of branches, with a different result being recorded in each branch.

This is so-called **many-worlds interpretation** of quantum theory.

Relative states

Everett insisted that pure Schrodinger wave mechanics is all that is needed to make a complete theory.

Thus, wavefunction obeys deterministic, time-symmetric equations of motion at all times in all circumstances. Initially, no interpretation is given for wavefunction; rather, the meaning of wavefunction must emerge from formalism itself. Without the collapse of the wavefunction, the measurement process occupies no special place in theory. Instead, the results of the interaction between a quantum system and an external observer are obtained from properties of a larger composite system formed from them.

In complete contrast to special role given to observer in von Neumann's and Wigner's theory of measurement, in Everett's interpretation the observer is nothing more than an elaborate measuring device.

In terms of the effect on the physics of quantum system, a conscious observer is no different from an inanimate, automatic recording device, which is capable of storing an experimental result in its memory.

The **relative state** formulation is based on properties of quantum systems which are composed of smaller sub-systems. Each sub-system can be described in terms of some state vector which, in turn, can be written as linear superposition of some arbitrary set of basis states. The vector space of composite system is a product of vector spaces of sub-systems. If we consider simple case of 2 sub-systems, then the overall state vector of the composite system is a giant linear superposition of terms involving all parts of both sub-systems.

The end result is a giant entangled state, where every property of one sub-system is entangled with all other properties of the other sub-system.

We can see more clearly what this means by looking at specific example.

Consider once again the interaction between a measuring device and a simple quantum system, which possesses just two eigenstates. The measuring device may, or may not, involve observation by human observer.

From previous discussions, can write the state vector of the composite system (quantum system + measuring device) as

$$|\Phi\rangle = c_+|\psi_+\rangle|\phi_+\rangle + c_-|\psi_-\rangle|\phi_-\rangle$$

As before, $|\psi_+\rangle$ and $|\psi_-\rangle$ are measurement eigenstates of quantum system and $|\phi_+\rangle$ and $|\phi_-\rangle$ are the corresponding states of measuring device (different pointer positions, for example) after interaction has taken place.

Everett's argument is that we can no longer speak of the state of either the quantum system or the measuring device independently.

However, can define states of measuring device **relative** to those of quantum system as follows:

$$|\Phi^+_{REL}\rangle = c_+|\phi_+\rangle$$

$$|\Phi^-_{REL}\rangle = c_-|\phi_-\rangle$$

and

$$|\Phi\rangle = |\psi_+\rangle|\Phi^+_{REL}\rangle + |\psi_-\rangle|\Phi^-_{REL}\rangle$$

The relative nature of the states is made more explicit by writing expansion coefficients c_+ and c_- as amplitudes:

$$c_+ = \langle\psi_+,\phi_+|\Phi\rangle \quad , \quad |\Phi^+_{REL}\rangle = \langle\psi_+,\phi_+|\Phi\rangle|\phi_+\rangle$$

$$c_- = \langle\psi_-,\phi_-|\Phi\rangle \quad , \quad |\Phi^-_{REL}\rangle = \langle\psi_-,\phi_-|\Phi\rangle|\phi_-\rangle$$

where

$$\langle\psi_+,\phi_+| = \langle\psi_+|\langle\phi_+| \text{ and } \langle\psi_-,\phi_-| = \langle\psi_-|\langle\phi_-|$$

Everett went on to show that the relative states formulation of quantum mechanics is entirely consistent with the way quantum theory is used in its orthodox interpretation to derive probabilities. Instead of talking about simple amplitudes and probabilities, it is necessary to talk about conditional probabilities, which is the probability that a particular result will be obtained in a measurement given certain conditions.

The name is different, but procedure is same.

All this is reasonably straightforward and non-controversial. However, the logical extension of Everett's formulation of quantum theory leads inevitably to conclusion that, once entangled, relative states can **never** be disentangled.

The Branching Universe

In Everett's formulation of quantum theory, there is no doubt as to reality of quantum system. Indeed, the theory is quite deterministic in the way that Schrodinger had originally hoped. Given a certain set of initial conditions, the wavefunction of quantum system develops according to quantum laws of motion. The wavefunction describes the real properties of a real system and its interaction with a real measuring device so that all speculation about determinism, causality, quantum jumps and collapse of wavefunction is unnecessary.

However, restoration of reality in Everett's formalism comes with a fairly large trade-off.

If there is no collapse, each term in the superposition of the total state vector $|\Phi\rangle$ is real, i.e., **all experimental results are realized.**

Each term in the superposition corresponds to a state of the composite system and is an eigenstate of observation. Each describes a correlation of the states of the quantum system and the measuring device (or observer) in the sense that $|\psi_+\rangle$ is correlated with $|\phi_+\rangle$ and $|\psi_-\rangle$ with $|\phi_-\rangle$. Everett argued this correlation indicates that observer perceives only one result, corresponding to a specific eigenstate of observation.

In his July 1957 paper, he wrote:

> Thus with each succeeding observation (or interaction), the observed state **branches** into a number of different states. Each branch represents a different outcome of measurement and a **corresponding** eigenstate for [composite] system. All branches exist simultaneously in superposition after any given sequence of observations.

Thus, in the case where an observation is made of the polarization state of a photon known to be initially in a state of 45°-polarization, the act of measurement causes universe to split into two separate universes.

In one of these universes, an observer measures and records that photon was detected in a state of vertical polarization. In the other, the same observer measures and records that photon was detected in a state of horizontal polarization. The same observer now exists in two distinct states in two universes.

Looking back at paradox of Schrodinger's cat, we can see that difficulty is now resolved. The cat is not simultaneously alive and dead in the same universe, it is alive in one branch of the universe and dead in the other!

With repeated measurements, the universe, together with observer, continues to split. A repeated measurement for which there are two possible outcomes continually splits the universe. The path followed from beginning of **tree** to the end of one of its branches corresponds to a particular sequence of results observed in one split universe.

In each branch, the observer records a different sequence of results. Because each particular state of observer does not perceive universe to be branching, the results appear entirely consistent with the notion that wavefunction of the original 45°-polarized photon collapsed into one or the other of two measurement eigenstates.

Why does the observer not retain some sensation that the universe splits into two branches at moment of measurement? The answer given by the proponents of the Everett theory is that laws of quantum mechanics simply do not allow the observer to make this kind of observation.

DeWitt argued that if splitting were to be observable, then it should be possible in principle to set up a second measuring device to obtain a result from memory of first device which differs from that obtained by its own direct observation.

Wigner's friend could respond with an answer which differs from one that Wigner could check for himself. This not only never happens (except where a genuine human error occurs) but is also not allowed by the mathematics.

The branching of the universe is unobservable!!!

Not very satisfying at all!!