The Measurement Problem in Quantum Mechanics and Interpretations of its meaning

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Abstract

We all have a classical prejudice that a measurement process should always be a pure discovery process, that is, a process through which we would take knowledge only of what already exists, prior to its execution. For example, the output of rolling of a die. They are very special kind of measurements, as measurement processes generally involve not only a discovery aspect but also a creation aspect. This is so because measurements can generally also change the state of the entity under consideration. The creation aspect is inherent in the quantum measurement processes and cannot be reduced to a mere disturbance effect: it would be an aspect of a more fundamental nature, which cannot be eliminated by a technological improvement. Quantum measurement would not be only about the properties it actually possesses, but also about the properties it is able to acquire, through the observational process. Quantum mechanics is a probabilistic theory that does not describe individual microscopic events with complete certainty, yet when we perform a single measurement, we find a well-defined outcome. The measurement problem in quantum mechanics is the problem of how (or whether) a wave function collapse occurs when a measurement is made. The inability to observe such a collapse directly has given rise to different interpretations of quantum mechanics and poses a key set of questions that each interpretation must answer. This problem has been studied for many years and here I have presented a review of the possible interpretations and solutions to this problem and how it impacts the very foundation of quantum mechanical theory itself. I start with an overview of how quantum mechanical phenomenon are traditionally described via theory and how is that related to the measurement problem. I later describe how can we interpret this problem and threw some light on the alternative reasonings and possible solutions.

I. INTRODUCTION

The elementary constituents of matter, often called particles, have properties that are described by mathematical objects called wave-functions developed in the form of differential equations by Erwin Schrödinger in 1925 . They are only a tool by help of which we calculate what we do observe. To make such a calculation, quantum theory uses the following postulates [1]: (i) Schrödinger's equation: As long as we do not measure the wave-function, it evolves according to this equation which guarantees that the probabilities computed from the wave-function will always add up to one (as they should). Schrödinger equation is linear, implying that if you have two solutions to this equation, then any sum of the two solutions with arbitrary pre-factors will also be a solution.
(ii) Born rule: It gives the probability of getting a specific measurement outcome from the wave-function. It says that the probability of a measurement is the absolute square of that part of the wave-function which describes a certain measurement outcome, say momentum in x-direction.
(iii) Measurement postulate: It describes the collapse of a wave function when a measurement is made- the probability of what you have measured suddenly changes to 1! This is a necessary requirement to describe what we observe. We never observe a particle that is 50 % measured.
The measurement postulate is incompatible with reductionism. The behavior of a large thing, like a detector, does not follow from the behavior of the small things that it is made up of. It makes it necessary that the formulation of quantum mechanics explicitly refers to macroscopic objects like detectors, when their behavior should really follow from the theory.

II. FOUNDATIONS OF QUANTUM MECHANICS AND THE MEASUREMENT PROBLEM

1. **What are the possible interpretations of quantum mechanical phenomenon?**
Copenhagen interpretation of quantum mechanics (which we discussed above) assumes that the physical systems generally do not have definite properties prior to being measured, and quantum mechanics can only predict the probability distribution of a given measurement's possible results. The act of measurement affects the system, causing the set of probabil-

ities to reduce to only one of the possible values immediately after the measurement. [2] Schrödinger came up with a thought experiment. He imagined a situation in which you set up a macroscopic system like a cat, link its death to a quantum event, and then carefully avoid any measurement of its state. Now, Copenhagen interpretation tells that this cat would remain in superposition of alive and dead until measured (i.e., until the box was opened), which is absurd. If the box is made transparent, then Schrödinger's thought experiment simply does not work. The state of the cat is being constantly measured (we can look at it) and so it will either die or not. The box has to be opaque to all physical influence and environment. [3] The main question is that at what point, or scale, do the probabilistic rules of the quantum realm give way to the deterministic laws that govern the macroscopic world? Copenhagen interpretation is now outdated and most contemporary interpretations of quantum mechanics appeal to notions like decoherence and many-worlds interpretation (which I have discussed in later sections) that does not involve the concept of an observer. The act of observation does not have any effect, so the point is moot. Neither the cat nor the experimenter are observers in the Copenhagen sense.

2. **What is quantum measurement and the measurement problem?**

It is an experimental situation in which a physical entity undergoes an indeterministic and irreversible change called the collapse of the wave function or reduction of the state vector. The existence of such changes is considered to be a problem because even if we perfectly know the initial state of the entity, that is, its state before the measurement, we cannot predict with certainty what will be its final state at the completion of the measurement process. The best we can do is to attach probabilities to the different possible final states using the Born rule. Another issue with the measurement postulate is that the update of the wave-function is incompatible with the Schrödinger equation. If you have two different states of a system, both of which are allowed according to the Schrödinger equation, then the sum of the two states is also an allowed solution. The best known example of this is Schrödinger's cat, which is a state that is a sum of both dead and alive. Such a sum is known as a superposition state. In reality, we observe a cat that is either dead or alive. This is the precise reason we need the measurement postulate. Without it, quantum mechanics would not be compatible with the observation. [4]

III. POSSIBLE SOLUTIONS TO THE MEASUREMENT PROBLEM

1. Many-worlds Hypothesis Collapse of the wave function presents a problem for deterministic physics. One solution is to not collapse the wave function, rather split the reality. Two views of reality are confronted: a many-worlds view, in which all possible outcomes of a quantum measurement are always actualized, in the different parallel worlds, and a one-world view, in which a quantum measurement can only give rise to a single outcome. Macroscopic systems exhibit irreversible behavior (entropy) that prevents the reconnection of past worlds and present the observed world as real to individuals, whereas for microscopic systems, many worlds does not allow communication between the worlds, but their existence can be tested in two slit experiments (the other worlds are doing the interfering). So, in the Multiverse view, when a measurement system and a measured entity interact, they become entangled; the entanglement is the expression of a superposition of different states, quickly evolving, through the process called decoherence, into a superposition of non-interfering alternatives; these alternatives, or outcomes, all describe actual events, coexisting in different worlds. No real collapse would take place. The multiverse would be described by a single state vector called the universal wave-function, evolving according to the Schrödinger equation, or to some linear generalization of it. [5]

2. Decoherence It is a process in which a quantum particle becomes entangled with the many particles of a much larger environment. Decoherence happens if a quantum superposition interacts with its environment. This interaction with the environment eventually destroys the ability of quantum states to display typical quantum behavior, like the ability of particles to create interference patterns. The larger the object, the more quickly its quantum behavior gets destroyed, they no longer have a quantum superposition. Instead, you have a distribution of probabilities called mixed states. Decoherence does not exactly solve this problem.

3. Hidden Variable Theory Critics believed that the probabilities of quantum theory are merely expressions of our ignorance. This theory assumes that far below the quantum level lies deterministic parameters, unseen to the observer, that controls the observed quantum numbers. Many eminent physicists, including Einstein believed that if the initial values of the hidden variables were known, it would be possible to predict exactly which nuclei would decay. One obvious flaw was that it could not explain the interference of electrons in double slit experiment. To explain that interference occurs only when the other slit is open, it is necessary to postulate a special force on the electron which exists only when that slit is open. Such artificial additions make hidden variable theories unattractive. To sum up, macroscopic physics states that all variables are there, just hard to measure, but Copenhagen interpretation states that there are no hidden variables and randomness is fundamental. [6]

4. New Dynamics The best known of these is the Ghirardi–Rimini–Weber theory, or GRW. It suggests that a quantum system will spontaneously undergo wave collapse purely of its own accord, without any need to engage in the mysterious measurement interaction. The probability of this collapse for a single quantum particle is very small, so we do not notice the process on the atomic scale. However, once we assemble many particles, then all it takes is for just one to collapse. That then triggers collapse among the remaining particles. While it is unlikely that any specific particle in a macroscopic body will collapse, it is very likely that one of the very many in the body will collapse. Thus, macroscopic bodies, consisting of very many particles, are extremely unlikely to persist in superpositions. They are almost certainly always in their collapsed states. The principal difficulty with this approach is that no one is able to say just which of the many possible slight changes is the correct one.

IV. CONCLUSION

Some define the problem of measurement simply as the logical contradiction between two laws describing the motion of quantum systems; the unitary, continuous, and deterministic time evolution of the Schrödinger equation versus the non-unitary, discontinuous, and indeterministic collapse of the wave function, but the most contemporary interpretations of quantum mechanics appeal to notions like decoherence and many-worlds interpretation that does not involve the concept of an observer.

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