The inconsistencies of the many worlds interpretation as a possible evidence of the incompleteness of the quantum mechanical wave function

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The quantum mechanical state vectors (or wave functions) as solutions of the Schrodinger equation evinces a physical duality or simultaneous reality as manifest through the famous measurement problem. There have been several interpretations to explain this duality, but none have seen full consensus among physicists. The Copenhagen interpretation, which is at least to some extent the most widely accepted interpretation has the 'collapse' of the wave function (or state vector reduction) during measurement as a possible narration to circumvent the problem of measurement, yet, it does not attribute a physical reality to the wave function. Moreover, the idea of measurement having a role on defining reality shakes the very foundation of classical physics. On the other hand, though mathematically sound, 'the splitting of the universe' in the Many Worlds Interpretation (MWI) lacks realistic and philosophical elegance verging on challenging the very 'common sense'. The MWI primarily hinges on the duality of the Schrodinger equation's solution, in the premise of which it seems to be correct. The drawbacks of MWI, especially its lack of any realistic consequence and its inconsistencies evince that the quantum mechanical wave function may not be a complete representation of the physical reality associated with that particular system under consideration. We illustrate this with our own original thought experiments inspired by the MWI's original thought experiment.

Keywords: many worlds interpretation, Copenhagen interpretation, duality, completeness

I. INTRODUCTION

The Rutherford atomic model proposes that the electron revolves around the nucleus in elliptical orbits. In the pre-quantum era it was believed that the electron must emit light as per the electrodynamics of the situation. But Quantum mechanics shows that the Hamiltonian of the atom does not change with time, unless there is an external intervention (with the exception of spontaneous emission) [1, 2]. A quantum state exists in its most general form as a superposition of several states. Whenever you make a measurement on a particular state, you get a probabilistic value corresponding to to the quantum mechanical wave function of that particular state. This is the indeterminacy of the time independent solution to the Schrodinger equation, while the time dependent solution will take an Eigen value (observable) of the system, and the system would evolve in time.

The indeterminacy has historically resulted in a lot of debates, that led not just to key understanding of quantum mechanics, but which raised questions on the concept of reality as we perceive it. There are three major common schools of thought when it comes to interpretations of the probabilistic results of quantum mechanics [3–5, 15] - the realist, the orthodox and the metaphysical. The realist argument is the classical physicist's favorite one. The quantum states of a system exist even prior to a measurement and there is some hidden variable which results in the probabilities. But, Bell's theorem followed by Aspect's seminal experiment [6] and other experiments [7–10] have argued that no such hidden variable can exist [13]. In the metaphysical interpretation, this and other quantum paradoxes [14, 47] are considered to be a consequence of human consciousness by certain physicists [4, 11, 12, 20]. But as per one of the most commonly accepted interpretation(orthodox), the Copenhagen interpretation (CI) [15] where the indeterminacy is due to the measurement. Consider an electron revolving around a nucleus with no disturbance, but when you measure an attribute of the electron, say a component of the spin in a particular direction, you get a certain value with a probability for the same and it will evolve in that state continuously, if you leave it as it is. But once again if you measure a spin in a different direction, you may get a new value for the electron spin in that direction with a different probability, so now the electron will evolve with that particular spin. Hence, we may conclude that the measurement causes the electron to attain that particular eigen value or observable. As per the CI, the electron lives in a superposition of several possible states and the wave function 'collapses' to a particular state when measured. The main criticism against CI is that it reduces physical reality into an observer created one, thus smuggling in subjectivity into physics. [16–19, 24]. Subjectivity in physics, at any level becomes untenable as it goes against the basic tenets of physics or reality. It is almost akin to saying that the moon exists only when you look at it [21].

Such conundrums are not limited to CI alone, but al-

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most all the interpretations are associated with some type of 'weirdness' [22, 23]. In addition, a good number of the interpretations fail to keep intervention of the observer and hence, the role of consciousness at bay [24]. Even after over a century of research, the physics world has not come to a consensus on the exact interpretation of quantum mechanics. The most compelling reason for the study of the interpretations of quantum mechanics is mainly the understanding of quantum mechanics itself through the resolution of its paradoxes [24]. As a spin off, it even throws light into modern applications of quantum physics including quantum computing [32, 33].

Among the main interpretations which attempt to restore the classical concept of physical reality is the Many Worlds Interpretation (MWI) [31]. The MWI tries to answer the contradiction between the probabilistic solution to the Schrodinger equation and the time dependent part which is deterministic in nature in a completely different way. Imagine you are in possession of an atom in which an electron is 'revolving around' the nucleus. Your picture is that of a continuous evolution of the electron wave function. Then, your friend serendipitously makes a measurement and obtains an outcome with a particular probability value for one of its states, thereby creating new branch(es) of the world. Thus the world, as per MWI, splits into two or more parallel universes with each measurement!. This splitting of MWI was proposed as a supposed alternative to the collapse of wave function or state vector, where instead of the wave function collapsing into one of the many possibilities, the measurement splits the world into two or multiple worlds, with each measurement. Each of those worlds is associated with a 'Universal Wave function/state vector', thus the MWI tries to espouse a clear physical state rather than a mere mathematical record in contrast with the CI.

In addition, the CI or other 'single world interpretations'(generic term for non many world interpretaions) [25] in the context of quantum locality fails to give any viable explanation for quantum entanglement, while MWI provides a potential answer to understanding quantum entanglement. In single world models, Quantum non locality is suggested as one of the basic axioms of quantum mechanics [36]. Quantum non local entanglement experiments in the past were restricted to the laboratory [6, 8–10]. The most recent ground breaking experiment confirms quantum entanglement at a much larger scale [37]. The assumption of transmission of signals between entangled quantum states violates special relativity explicitly [38]. Though it is proven that such transmissions cannot be faster than light (FTL) there is a tension between the special theory of relativity and quantum mechanics. Special relativity is local and quantum entanglement is not. In Ref.[35] Tipler says quantum non locality may be an evidence to MWI. Corresponding to the measurement of each of the correlated pair of spins of entangled quantum particles the universe splits into separate ones, where the spins are local. In this case there is no explicit contradiction with special relativity, which makes the MWI an interesting case indeed. The reason for this is quite obvious, other than quantum mechanics, the idea of physics is very much local in nature.

At this point it becomes greatly relevant to note that Albert Einstein in Ref. [34] considered non locality as a problem which questioned the very veracity of quantum mechanics. In it's abstract itself we can see that Einstein had opined that either quantum mechanics is incomplete or results in a concept of simultaneous reality. Now after all these years we have MWI catching up. The concept of simultaneous reality is very much analogous to the split worlds in MWI as noted by Ref.[35]. It had long been argued that Bell's Theorem [13] has explicitly expostulated all possibilities of hidden variables, that could possibly explain quantum entanglement. It also suggests that the quantum wave function provides a complete picture. But that is no last word, there have been arguments against the theorem, one of the latest ones, using consistent histories interpretation [20, 48] to show the problems in its deviation of Bell's theorem [39]. There have been numerous hidden variable theories [40–43]. In Refs.[41, 44–46] one can see the problems in disproving local hidden variable theory experimentally indicating that the completeness of quantum mechanics is not sacrosanct and might indicate the need for hidden variables to ensure local realism. MWI is a direct consequence of the assumption of completeness of the quantum wave function. There are many ways to prove MWI as being incorrect as we shall see in Sec.II. We argue in this paper that the incorrectness of MWI is possibly a proof to the fact that the time dependent wave function might not represent a full description of the system under consideration. We will first see the criticisms against the MWI. Then we will revisit Everett's original thesis [31] in Sec.III.In Secs. IV and V we will present our own thought experiments to fill in the gaps created by the MWI. After that we will conclude our discussion in Sec.IV.

II. CRITICISMS AGAINST MWI

The main criticism against the MWI is the non realizability of the Universal wave function physcially [25, 26]. This applies to the several modified versions for the MWI as well, which have tried to address this but failed. This is like criticising the MWI for the same reasons as the CI-viz. physically non realizable nature of wave function itself and the general non adherence of Quantum mechanics to reductionism [50] in general. In addition in Ref.[25] one of the main criticisms is that MWI fails to live up to the expectation of providing a mathematically elegant and Lorentz co variant and universally applicable version. The expectation of MWI to replace CI has failed considerably.

Often the proponents of the many worlds interpretation argue that the rejection of the many worlds interpretation should not be on grounds that it sounds weird or crazy [27]. But, in physics, theories are to be accepted only on the basis of experimental validity - or the argument that the splitting of universe must have some observable effect on the current universe we live in. An acceptable theory must be falsifiable [30]. Every time when a quantum experiment is carried out or an observation is made, the universe splitting into many and that we have never had any observational impact on our universe when the universe splits is indeed crazy. There are indeed many commonsensical and realist reasons to reject the MWI [28, 29]. In fact Ref.[28] calls the MWI a 'wacky' theory. 'Notorious' is the word used in Ref.[29].

This is not to suggest that the proponents of MWI have done something absurd, no not at all. What we posit is that, their out of the box thinking has given us new critical perspectives to look at the basic axioms of quantum mechanics. It becomes very clear with these criticisms, that MWI will never represent the world as it is. But, the main argument on which the MWI is based on is not negated directly in any of these comprehensive criticisms. That is, the dual physics of unitary evolution (time dependent) and state vector reduction (time independent) solutions of the Schrodinger equation representing completely different paradigms of the same picture is not negated directly. This makes us come to the following conclusion, that the basic premise of MWI is a direct consequence of this duality and the incorrectness of the results of the MWI only raises serious questions on weather the quantum mechanical wave function is complete.

III. MWI'S ORIGINAL THOUGHT EXPERIMENT: A REVISIT

Since we will be developing our own thought experiments which are inspired by the original thought experiment of Everett in Ref.[31], let us reproduce their original thought experiment for the benefit of the reader. There are quite a few modifications of the MWI [25, 26], all of them basically depend upon this thought experiment at the very begining of Ref.[31].

Consider two quantum mechanics experts A and B and A is inside the room carrying out his measurements on a quantum mechanical state Ψ which exists as a super position of several sub states ψ_i, with a total of n sub states. On each measurement A gets a probability $|c_i|^2$ of the quantum state living in one of the sub states.

$$\Psi = \sum_{n=1}^{n} c_i \psi_i \tag{1}$$

$$\sum_{n=1}^{n} |c_i|^2 = 1 \tag{2}$$

Imagine A notes his measurements and the probabilities. On the other and B who is standing outside, is in full possession of the entire system. Entire system refers to the room, A and his experiment. In concrete mathematical sense, B is in possession of the time dependent solution to the Schrodinger equation $\Psi(t)$ and the wave function evolves in time. He records its behaviour, for say a week.

The only logical conclusion is that the total amplitude of the complete wave function that B possesses, is the sum of the amplitudes of the of the discrete probabilistic measurements made by A (This part is validated if you consider the concept of A's sum of probabilistic amplitudes Eqn.2 and B's normalization of the wave function which are both 1).

But, B possesses the complete wave function only until the current measurement of A. When B opens the door (dramatically) he sees that A gives a probabilistic result $|c_i|^2$ of Ψ being in some ψ_i. Thus the existence of A is due to the 'mercy' of B, that is if B had not opened the door A's result would not exist. Until B opened the door he had a deterministic view of the wave function. When he opened the door, the probabilistic measurement of A comes into existence, thereby creating a new world. Thus there are now two worlds, one where the wave function is deterministic and another one where it is probabilistic in nature.

The above thought experiment and the conclusion is based on the physical duality already forming the basic tenet of quantum mechanics as it is existent today. The MWI is only a manifestation of this duality. If the above thought experiment were correct, then you and I will not exist unless some guy doing a quantum mechanics experiment opens his door. This becomes more or less like the simulation hypothesis (see for example [49]), that is the whole Universe is controlled by one person, which is crazy. But the physical duality (or simultaneous reality [34]) gives us no other option but to conclude that if the wave function Ψ were to represent a full description of the quantum mechanical system, then the MWI is the consequence. But we know that the MWI is wrong as we have seen in Sec.II, so there is only one conclusion, the one already mentioned in [34], that the quantum mechanical wave function is not complete in its description of whatever it is supposed to represent. We will attempt to validate this further using our own thought experiments in the subsequent sections.

IV. THE SUPEROBSERVER THOUGHT EXPERIMENT

Let us modify Everett's thought experiment. Instead of B being outside the room, let B be inside the room itself. Let us consider the room having two floors. Let B be the super observer (S) looking from above. At the floor below, the quantum state as in Eqn.1. But instead of just A, let us consider a large number of observers who are making measurements . Let there be a number of observers $A_1, A_2..A_n$ (As) who are making observations on the quantum system represented by Eqn.1. Each of those observers simultaneously measure the system to be in $\psi_1, \psi_2..\psi_n$ with probabilities $|c_1|^2, |c_2|^2..|c_n|^2$ which follow initially. But, after a small amount of time t, for each of those observers, the system will evolve in a unitary way : $\psi_1(t) = \psi_1 e^{\frac{-iE_1 t}{\hbar}}, \psi_2(t) = \psi_2 e^{\frac{-iE_2 t}{\hbar}}..\psi_n(t) = \psi_n e^{\frac{-iE_n t}{\hbar}}$ (Where E_i represents the eigen value or observable of the measurement). Now, for each of those observers, their own quantum wave should represent the full picture of the system.

But S is watching all this from above. The super observer(as the name suggests), will observe all of the observers below making their respective measurements. The super observer collects the initial probabilistic measurements of the observers below and thus the initial wave function at time t=0 is as in Eqn.1. At a later time t, S collects the wave functions $\psi_1(t), \psi_2(t)..\psi_n(t)$, which the observers below possess, each of which only represent a part of the complete picture (according to S). Which means all of them are only a part of the total wave function $\Psi(t)$, which have probabilities $|c_1|^2, |c_2|^2..|c_n|^2$ as in Eqn.3.

$$\Psi(t) = \sum_{n=1}^{n} c_i \psi_i e^{\frac{-iE_i t}{\hbar}} \tag{3}$$

Where E_i represents the Eigen value or observable of the measurement. That is at a later time t, the probability to find the system in any one of $\psi_1, \psi_2..\psi_n$ is going to be $|c_1|^2, |c_2|^2..|c_n|^2$. This is like the weighted sum total of the time wave functions of the observer below, if we assume the time elapsed t, the same for every one. For every increase in t, As update S with the wave functions.

So there is an essential contradiction here, the observers $A_1, A_2..A_n$ each have a separate picture. There is going to be a big melee in the bottom floor where each of the observers are going to argue that their picture is the complete one and represents the entire system. While S will argue that he is truly in possession of the entire system Eqn.3 and thus possesses the complete wave function. In fact it is S who is indeed correct (mathematically). And each of the observers below only represent the system in totality together. Thus As are wrong to suggest that each of their time evolved wave functions represents the full system. So much for wishful thinking!. All of them are correct in their own perspectives (represent the full system), if the current quantum mechanics state of the art is to be believed as it is. But clearly this poses a major contradiction in terms of completeness of the wave function.

The results are in direct contradiction of the world splitting as assumed by Everett. If each of the observers in the bottom floor were to split into separate worlds according to the MWI, then according to S, all their worlds split right in front of his eyes. This will never happen practically. But one more thing, S needs the time evolved wave functions continuously from the observers below him to construct his full wave function as in Eqn.3, thus all those observers are very much part of his world, hence the world can not split even by the logic of MWI. Because if it splits S can not build his wave function, but he does build it.

V. COMPOSITE SYSTEMS THOUGHT EXPERIMENT

In this 'gedanken' experiment, let us closely follow the footsteps of Everett, but let us consider a simple yet composite system. This thought experiment is inspired by problem 3.32 in Ref.[5]. Instead of following the 'Shut up and calculate' recipe [27] as is common in most quantum mechanics text books, we will take into consideration the interpretational consequence of such a system.

Let us start with A, who is inside a room and B who is outside the room. B is in possession of the simplest superposed wave function.

$$\Psi = \frac{1}{\sqrt{2}}\psi_1 + \frac{1}{\sqrt{2}}\psi_2 \tag{4}$$

For B the wave function will evolve as

$$\Psi = \frac{1}{\sqrt{2}}\psi_1 e^{\frac{-iE_1 t}{\hbar}} + \frac{1}{\sqrt{2}}\psi_2 e^{\frac{-iE_2 t}{\hbar}} \tag{5}$$

With a probability of 0.5 of being in either one of the sub states. Here E_1 and E_2 are the eigenvalues or observables associated with the measurements.

But in the most general form a quantum mechanical state can be expressed as a linear combination or superposition of other states. This goes not just for Ψ in Eqn. 5 but for ψ_1 and ψ_2 as well as in Equations 6 and 7

$$\psi_1 = \frac{3}{5}\phi_1 + \frac{4}{5}\phi_2 \tag{6}$$

$$\psi_2 = \frac{4}{5}\phi_1 - \frac{3}{5}\phi_2 \tag{7}$$

This same formulation can also be written as

$$\phi_1 = \frac{3}{5}\psi_1 + \frac{4}{5}\psi_2 \tag{8}$$

$$\phi_2 = \frac{4}{5}\psi_1 - \frac{3}{5}\psi_2 \tag{9}$$

If A were to measure ψ_1 and ψ_2 he will get a probability of 0.5 for either of them. For B who is standing outside, the system evolves according to Eqn.5, where the probabilities of being in being in either ψ_1 or ψ_2 as 0.5. Until now the system is very much similar to Sec.III.

But, further considerations will show that A's picture is much more interesting. Let A measure for ψ_1 he gets ψ_1 with a probability 0.5. Now after this measurement the wave function is expected to live as in Eqn. 6. Now he measures ϕ_1 and the total probability of the system to be in ϕ_1 is $P(\frac{\phi_1}{\psi_1}) = (\frac{1}{2})(\frac{9}{25})$. The system after this measurement lives in the state ϕ_1. Now the probability of finding the state in ψ_1 and ψ_2 will be.

$$P(\frac{\psi_1}{\psi_1, \phi_1}) = (\frac{1}{2})(\frac{9}{25})(\frac{9}{25}) = 0.065 \tag{10}$$

$$P(\frac{\psi_2}{\psi_1, \phi_1}) = (\frac{1}{2})(\frac{9}{25})(\frac{16}{25}) = 0.125 \tag{11}$$

The probabilities measured are considerably different from what A measured for ψ_1 and ψ_2 initially, before he measured ϕ_1. Mathematically, this is a typical case of conditional probability. Quantum mechanically, the most natural narrative for this would be the CI's collapsible wave function. In addition, the other probabilities that can be associated with A's measurement of ψ_1 and ψ_2 are $P(\frac{\psi_1}{\psi_1,\phi_2}), P(\frac{\psi_2}{\psi_1,\phi_2}), P(\frac{\psi_1}{\psi_2,\phi_1}), P(\frac{\psi_2}{\psi_2,\phi_1}), P(\frac{\psi_1}{\psi_2,\phi_2})$ and $P(\frac{\psi_2}{\psi_2,\phi_2})$, depending upon the sequential order of his choice. These probabilities are all completely oblivious to B who is outside, all he is aware of is ψ_1 and ψ_2 both at 0.5. So B's wave function in Eqn.5 is not necessarily a complete description of the system, unlike Sec.III. This kind of composite situation where the same wave function can have different probabilites, depending upon the sequence of measurement can be better explained by the collapsible wave function than the MWI, there by exposing the inconsistencies of the MWI. But it also raises interesting questions on the wave function being a complete description of the system under consideration.

VI. CONCLUSIONS

Reductionism is the notion wherein everything in the world when decomposed into smaller parts, the constituents will follow the same laws as does the object itself. Reductionism has a very deep root in physics [50]. Quantum mechanics grossly violates the principles of reductionism. In every interpretation of quantum mechanics there is a considerable amount of controversial weirdness. No matter what interpretation one takes there is an element of subjectivity, which makes quantum mechanics so disturbing and intriguing at the same time. A metaphor 'the moon exists only when you look at it', that can be associated with quantum mechanical measurements, makes the whole subject queer.

Years back Albert Einstein [34] had given a choice between the incompleteness of the quantum mechanical wave function and simultaneous reality. The MWI seems to be an off shoot of this simultaneous reality. The MWI does try to do away with the collapsible wave function, but in Sec.V we have seen that the MWI does not accomplish this. We have seen that the critiques in Sec.II have conclusively proven that MWI does not represent physical reality by any means, hence it fails as a descriptor of the universe. In this paper, we have presented strong logical reasons to come to the same conclusions with the help of our own modified versions of Everett's original thought experiment, with different perspective and shown that branching of the world during quantum measurements leads to logical inconsistencies. The inconsistencies of the MWI my thus raise important questions on the completeness of the quantum mechanical wave function. Of course, the only way to prove that the wave function is incomplete in the purview of many of its paradoxes including non locality, is by conclusively proving the presence of hidden variables both theoretically and experimentally. We believe our work raises some interesting questions on the idea of quantum mechanical completeness, when you juxtapose it with MWI's inconsistencies.

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