Article

Proposal for Solving the Quantum Measurement Problem

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Abstract

The measurement problem is one of the greatest unsolved mystery of the foundations of quantum mechanics. This paper is an exploration of the underlying subtleties of this phenomenon from the standpoint of the quantum mechanical interpretations that are available to us at the moment. First, we revisit the infamous double slit experiment and contrast between the observer dependent and observer independent effects on the measurement process. In this regard, we have tried to establish a causal relationship between the observer's consciousness and the collapse of the wave function. The point is justified through the application of Godel's incompleteness theorems. Finally, we perform a thought experiment which shall validate our conclusions.

Keywords: Wave function collapse, superposition, observer effect.

1 Introduction and Summary

The measurement problem dates back to the initial days of quantum theory. Attempts to solve it include models of wave function collapse, several interpretations of quantum mechanics, theory of decoherence etc [1-14]. However, no single interpretation has been able to completely explain the various irregularities of the quantum world to complete satisfaction. Unfortunately, there is a lack of consensus for a single formalism, there exists between certain groups of physicists, a favouritism for a particular interpretation which sadly, is loaded with their own prejudices and biases. In science, calculations and interpretation should be kept on equal footing. Extreme notions such as shut up and calculate" must be avoided. A certain balance must coalesce the two into a complete and true picture of reality. In this paper, we keep our investigations grounded along these lines with the prime motive to carve out a clearer picture of the measurement problem. We have tried, to keep a check on our biases and have allowed the empirical evidence(s) lead the way, from which we have tried to map our ideas onto these empirical evidences.

2 Double Slit Experiment Revisited

Things happen pretty classically with the double slit experiment for mundane objects which seem to obey our Boolean logic and evolutionary intuitions, however things get more complicated as one transitions to the quantum realm. The Boolean logic of black or white breakdowns to give way to a much more balanced approach to thinking. Here we describe the experiment itself along with the actual experimental observations as empirical evidence. A stream of electrons passing through a double slit creates an interference pattern at the screen, i.e. they exhibit wave like properties as evident from the de Broglie hypothesis. Even if electrons are shot one at a time, it still results into an interference pattern which is startling [15, 16]. If we imagine what is really happening here, we would see, that the electron leaves as a particle, mutates into a probability wave, goes through both slits, interferes with itself and finally hits the screen.

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This seems outrageous! Probing into the underlying mathematical underpinnings would reveal that the scenario here is that the electron which is a wave packet with waves of different frequencies superposed and propagating with a group velocity, goes through both slits as different parts of the same probability wave and then recombines to form a localized particle and hits the screen. The equations further reveals that all the different possibilities of the electron going through the double slit is in superposition. If the electron is viewed as a probability wave, we have,

$$\psi(x) = \alpha\psi_a(x) + \beta\psi_b(x) \tag{2.1}$$

which represents the superposition state and the probability density is given by,

$$P(x) = \alpha\psi_a(x) + \beta\psi_b(x)^2 = \alpha\psi_a(x)^2 + \beta\psi_b(x)^2 + \alpha\beta^*\psi_a(x)\psi_b^*(x) + \alpha^*\beta\psi_a^*(x)\psi_b(x) \tag{2.2}$$

The above equation actually represents the quantum interference. Now, if we put a detector inorder to really know which slit the electron went through, the observations are breathtaking. We model the scenario by drawing contrast between the observer dependent (detector present) and observer independent (detector still present) effects. A thought experiment is also performed to visualize and clarify the conclusions.

CASE I (observer + detector): As mentioned above, quantum particles such as electrons or for that matter, things such as Bucky balls when shot towards a double slit, an interference pattern is observed which happens in the absence of a measuring device and which is simply impossible if the particles behave classically since the particle must have gone through a single slit and a single detector at an instant. Only waves exhibit the interference phenomenon and not classical particles such as cars, stars or any other macroscopic objects. In the case of macroscopic objects, the interference is not significant enough to be measured or detected. Classical particles are bounded in their own potential wells which constrains their behaviour to that of a localised particle whereas this is not true for objects which belong to the set of the quantum realm which unlike the classical particles exhibit a non local phenomenon therefore, behave as that of a wave which in turn explains the interference phenomenon. This clearly differentiates the two domain of reality, and establishes the impossibility of classical particle showing interference pattern. This leads to the conclusion that the electrons must have behaved like that of a wave while passing through the two slits. Naturally, this leads to the verification of this claim. In the case of quantum particles, if one of the detector is removed, the consequences remain unchanged and still there would be no interference phenomenon.

CASE II (only detector): Consider the situation where the observer is not present or is present indirectly in a way that he is not watching the experiment through his eyes. In this condition, as described by the mathematics, the electron passes through both the slits and detectors but still the interference pattern is absent. How come? This is strange! When the observer now observes the system, he sees the electron striking only one of the two detectors which indicates its definite location. In this case the detector is basically replacing the observer. At this point a question may arise as to why then the interference pattern disappears in the absence of an observer? The answer lies in the fact that the detector is already acting as a hindrance in the path of the electron causing the particle to change its behaviour.

According to Einstein-Podolsky-Rosen (EPR), physical reality is dependent on the ability to measure a system without disturbing it in any way [17]. In view of the aforementioned discussions on the observer dependent and observer independent effects, the situation is quite the opposite. The experimental observations are indicating without room for slightest doubt, that the conscious observer is playing a fundamental role in the measurement process and it is in regard with this fact that we now argue that there's a causality relation between the observer's consciousness and the collapse of the particle from a superposition of possibilities to an ontic state. This is achieved through the application of Godel's incompleteness theorems [18]. The real mystery in resolving the measurement problem is that we are lacking an ontology, a mechanism through which the transition from abstract mathematical construct to a physically realistic state is actually taking place. The transition (or collapse) can be shown explicitly as follows. We start with a superposition state of the form, say,

$$|\Psi\rangle = \sum_{\Phi} |\Phi\rangle \, \Phi\Psi \tag{2.3}$$

The above equation uses the identity operator $\hat{I} = \sum_{\Phi} |\Phi\rangle \, \Phi$ in some fixed orthonormal basis $\{ |1\rangle , |2\rangle , ..., |\Phi\rangle \}$ as follows:

$$|\Psi\rangle = \hat{I} \, |\Psi\rangle = \sum_{\Phi} |\Phi\rangle \, \Phi\Psi = \sum_{\Phi} (\Phi\Psi) \, |\Phi\rangle = \sum_{\Phi} a_{\Phi} \, |\Phi\rangle \tag{2.4}$$

where the quantum probability amplitudes have been set as, $a_{\Phi} = \Phi\Psi$. The Born rule can be used to compute the probability density, given by,

$$P(\Phi) = \Psi\hat{\mathbb{P}} \, |\Psi\rangle = \Psi\Phi\Phi\Psi = a^{*}_{\Phi} a_{\Phi} = a_{\Phi}{}^{2} \tag{2.5}$$

An act of observation (measurement) would reduce the superposition state to a definite eigenstate state represented by, $\sum_{\Phi} a_{\Phi} \, |\Phi\rangle \rightarrow |\Phi\rangle$ and now the state of the system at any future time would be determined by the Schrodinger evolution,

$$i\hbar \frac{d}{dt}(|\Phi\rangle) = \hat{H}(|\Phi\rangle) \tag{2.6}$$

where $\hat{H}$ is the Hermitian operator called the Hamiltonian. More details can be found in [19].

Godel's first incompleteness theorem states that [20], If T is a computably axiomatized, consistent extension of N, then T is undecidable and hence incomplete". In other words [21], Any consistent formal system F within which a certain amount of elementary arithmetic can be carried out is incomplete; i.e., there are statements of the language of F which can neither be proved nor disproved in F. The second theorem states that [21], For any consistent system F within which a certain amount of elementary arithmetic can be carried out, the consistency of F cannot be proved in F itself".

In [22], it was shown that Godel's theorems are applicable in the domain of physics in general and quantum theory in particular. Building on their results, we incorporate Godel's theorems into our system and establish a causal relationship between consciousness and the collapse of the wave function. To contrast this, let us show a proof by contradiction in which we put forward the proposition that, there exists no causal relationship between consciousness and the collapse of the quantum wave function. CASE II tells us that in the absence of a conscious observer, the particle passes through both the slits and is recorded by both the detectors as inferred from the mathematical calculations. However, when a conscious being is introduced into that bounded system, the wave function of the electron collapses and it strikes only one of the detectors. In other words, the particle is in a quantum superposition and is not localised until observed. This is a contradiction with our proposition, hence there must exist a causal relationship between consciousness and the collapse of the wave function. Godel's first theorem explains the main point here. If one cannot prove the influence of a conscious observer on the quantum measurement process, this does not in any case necessitates the falsehood of the claim. Here we take the causal relationship as an a priori statement in the form of an axiom which is well supported by the theorems proposed by Kurt Godel and then deducing the results which map onto the experimental evidences which have been performed and recorded over the past century since the dawn of this quantum enterprise itself and in some cases, long before that as well.

It is also found that Cochran's argument that elementary particles like electrons possess a rudimentary level of consciousness, a kind of self activity, supports our ideas and thoughts presented in the paper [23]. We now discuss what decoherence has to say about the measurement problem and why it doesn't really solve the problem [24]. We clarify the actual role played by decoherence in the process.

3 Decoherence and the Measurement problem

Proponents of the decoherence theory argue that it explains the collapse of the particle. The explanation goes along the following lines. The particle which is to be measured is interacted with another particle which disturbs the state of the first particle as part of the interaction process. As a result, the collapse of the first particle happens due to the particle which has been used to interact with it. But if this is the case, an attentive reader would ask then what is the reason behind the collapse of the measuring particle? We would need another measuring device to collapse it and then another apparatus to collapse the previous measuring device and this goes on and on in a chain called the von Neumann chain. The von Neumann chain can be explained mathematically in a beautiful way using the following array of equations [25],

$$|O\rangle \left(|M_o\rangle |F_o\rangle |W_o\rangle\right) = \left(|A\rangle + |B\rangle\right)\left(|M_o\rangle |F_o\rangle |W_o\rangle\right) \xrightarrow{t_1} \tag{3.1}$$

$$\left(|A\rangle |M_A\rangle + |B\rangle |M_B\rangle\right)\left(|F_o\rangle |W_o\rangle\right) \xrightarrow{t_2} \tag{3.2}$$

$$\left(|A\rangle |M_A\rangle |F_A\rangle + |B\rangle |M_B\rangle |F_B\rangle\right)\left(|W_o\rangle\right) \xrightarrow{t_3} \tag{3.3}$$

$$\left(|A\rangle |M_A\rangle |F_A\rangle |W_A\rangle + |B\rangle |M_B\rangle |F_B\rangle |W_B\rangle\right) \tag{3.4}$$

The above equation has taken into account the evolution of a system $|O\rangle = |A\rangle + |B\rangle$ and its measurement by Wigner and his friend. $|M_o\rangle$ is the initial state of the measuring device associated with the system. Now, an act of conscious observation by Wigner would collapse the superposition in the eqn. (6) to either of the states and thus the measurement would yield either $|A\rangle |M_A\rangle |F_A\rangle$ or $|B\rangle |M_B\rangle |F_B\rangle$.

On careful analysis, it is realised that the decoherence theory is basically talking about the mechanism of the collapse that would supposedly take place naturally by environment induced decoherence. Decoherence would collapse a particle naturally if left out for some period of time, maybe years. On the other hand, von Neumann's interpretation talks about an instantaneous collapse brought about by conscious observation. Where the former is talking about the how", the latter is answering the why", by establishing the necessary causality between the two phenomena which we showed earlier. Fortunately/Unfortunately, questions of such sort are philosophically laden but that does not imply that they are irrelevant to the progress of the scientific enterprise since they might act as an overarching guiding principle. Sometimes, one has to contend with such philosophically laden ideas and questions when grappling with them because they are, after all intimately entangled" together.

4 A Thought Experiment

Here we perform a simple thought experiment which is a variation of a similar one performed in the case of Schrodinger's cat [26]. We model the double slit experiment scenario in terms of a circuit diagram as shown in the figure below. In our model, the switch replaces the poison and bulb replaces the cat. The switch in this case acts naturally when electron wave passes through both the slits simultaneously. Then, using quantum logic gates, we analyse the information flow between the switch and the bulb in order to verify its correlation with the theoretical arguments and whether or not they are consistent within the framework. We start from the classical case. If classical balls are used instead of quantum particles, there would be no interference pattern. The circuit actually makes no sense in this particular case. We are mainly interested in how this classical behaviour transforms to the quantum regime.

Coming to the quantum regime, the bulb would glow if the circuit is fully complete. The state of switch-bulb system can be represented by the following entangled state,

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle \otimes |on\rangle + |1\rangle \otimes |off\rangle\right) \tag{4.1}$$

Also unless a rational quantum CNOT gate is performed between the switch and the bulb, the final state of the system would be given by the statistical mixture [26],

$$\rho = a^2 \, |0\rangle \, 0 \otimes |on\rangle \, on + b^2 \, |1\rangle \, 1 \otimes |off\rangle \, off \tag{4.2}$$

In the absence of a measuring device, an electron would pass from both the slits simultaneously, the circuit would be completed without any problem, the bulb would glow and thus an interference pattern would be formed as a consequence. Coming to the observer dependent case, the electron passes either from the first or from the second slit and not both simultaneously. As a result, the circuit remains incomplete, the bulb wouldn't glow and also the interference pattern vanishes. Note that we haven't made any major change in the system and have just introduced the observer into the picture. If we assume a priori that the consciousness model is correct as an axiom, the results we observe emerge automatically and they are in full agreement with empirical evidences as well as our thought experiment as presented here.

Lastly, we are left with the observer-independent case and which is also perhaps the most intriguing part. In this case, although the electron would pass through both the slits simultaneously, the circuit would be completed and the bulb would also glow but still the interference pattern would vanish. It is important to recall that this is something which is only perceived from the math and it is only when an actual observation is made by a conscious observer that the electron seems to strike a single detector which would also imply that it passes through a single slit rather than both simultaneously. This would mean that the circuit is not completed and also the bulb wouldn't glow when a conscious observation is made. A straightforward contradiction can be seen here. There is severe lack of correlation between what the math says and what is actually seen upon observation. A denial of the role of conscious observation at this point, if any, would seem to be brought about by force.

5 Conclusion

While researching for our paper, we got accustomed to some of the work other people have done or are doing along the similar lines, such as Penrose [27], Stapp [28] and Irwin [29] alongside many others. This paper is our introductory paper addressing the measurement problem. We have tried to make this paper self contained and elaborate at the same time just like other quantum physical objects- which is somewhat relevant afterall. We are looking forward to carry research along these lines in the future and also invite others who are thinking like us to join this journey.

Figure 1: Circuit Diagram: The figure shows an electron source through which electrons would initiate and pass through the double slits. Behind the slits, a circuit has been constructed consisting of a bulb. If electrons pass through both slits simultaneously, the bulb would glow otherwise it would remain off.

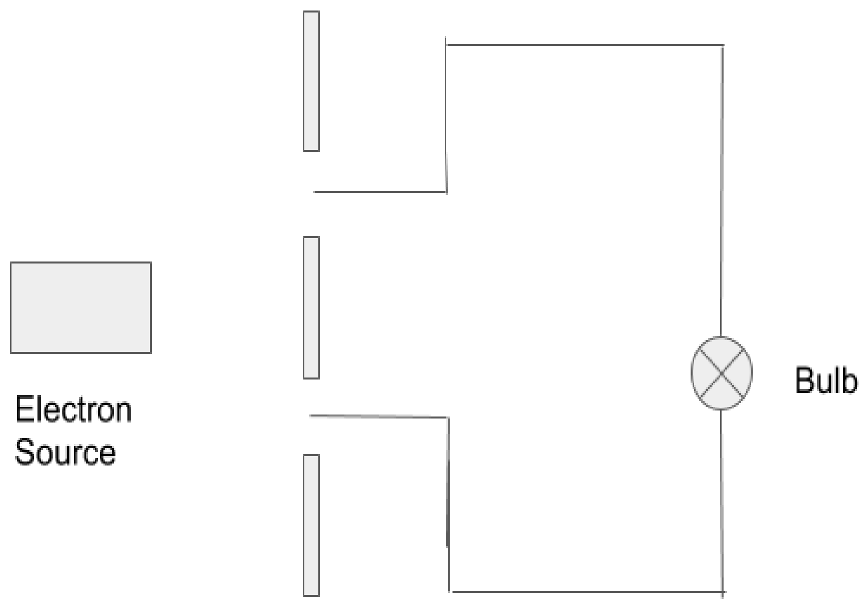
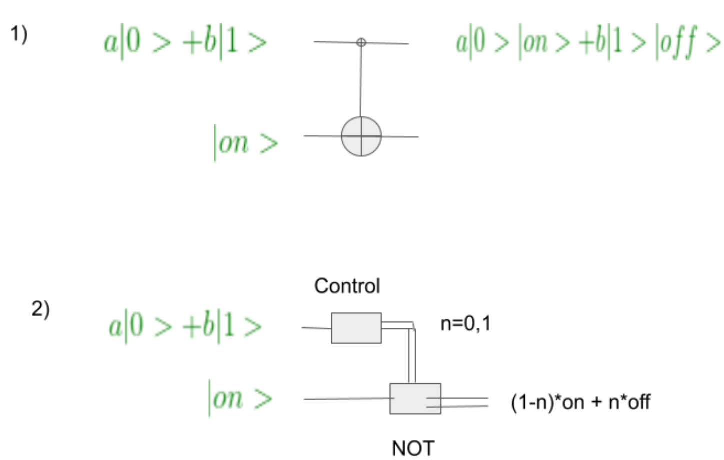


Figure 2: Quantum Network Model: The model reveals the information flow in the thought experiment. Part 1 of the figure represents the entangled switch-bulb system. Bulb in the initial state $|on\rangle$ is linked to the switch via a quantum CNOT gate resulting in the state given by eqn. (11). In the second part, the switch evolves freely to $a\,|0\rangle + b\,|1\rangle$ and is coupled to the bulb via a classical information channel.



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