The radically conservative view of the Many Worlds Interpretation of quantum mechanics

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This paper represents my own work in accordance with University regulations.

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Abstract

In this paper, I present a short introduction to the main findings of quantum mechanics, emphasizing the fundamental issue that arises when we consider an observer as part of the quantum mechanical system. I then shortly mention the different approaches to resolve this problem and construct a satisfactory theory of quantum mechanics. The core of the paper consists in a critical analysis of the so called Many Worlds Intepretation (MWI). The main objections to the theory are rejected, while still emphasizing the crucial assumption to regard the superposition of quantum states as a multiplicity of disjoint worlds. The argument of this paper is that this assumption is not granted and should make us question the extravagant and absurd results of this interpretation.

Quantum mechanics is the description of the behavior of matter and light in all its details, at the atomic level [1]. At these microscopic scales, nature behaves like nothing that we have ever had any direct experience about, in a seemingly pure indeterministic way. These findings are not only completely different from the classical prescription of physics, but they are, in many respects, absurd, as they contradict the deterministic logic that we have developed over the centuries and that in our world works so well, that we fail to imagine a different one. In fact, up until that moment, science stood on the assumption that if one were to find the exact laws of nature, we could predict precisely what will happen [1]. In other words, science regarded the universe to be deterministic. Through the several experiments performed at the microscopic scale, it turns out that it is seemingly impossible to predict precisely what will happen, all we can achieve is to predict the odds of the possible outcomes. Nevertheless, quantum mechanics is perhaps the theory that has had the greatest success in physics. There is yet no observation that tells against the theory, which in the last century, has helped us explain many things that were a complete mystery before its advent (e.g., the stability of atoms, spectral lines, chemical forces, black-body radiation, lasers, etc.) and played a pivotal role in the technological developments which distinguishes modern society.

In contrast with classical mechanics, which takes the state of a particle and hence all information about its current and subsequent motion, to be determined entirely by its position $x(t)$ and momentum $p(t)$ as functions of time, quantum mechanics takes as a postulate that the state of the particle is determined entirely by a abstract vector $|\Psi(t)\rangle$, so called particle *wavefunction*, in a infinite-dimensional Hilbert space [2]. As long as the system stays isolated, $|\Psi(t)\rangle$ evolves deterministically in accordance to the Schrodinger equation (SE):

$$i\hbar \frac{d}{dt}|\Psi(t)\rangle = H|\psi(t)\rangle \tag{1}$$

where the operator H corresponds to the Hamiltonian of the system [3].

Given the linearity of eq.1, for any complete compatible set of observables $\mathcal{O}$ in H, we can always reexpress $|\Psi(t)\rangle$ as a superposition of the eigenstates of $\mathcal{O}$ (ψ_i), according to [3]:

$$|\Psi(t)\rangle = \sum_{i=1}^{n} c_i |\psi_i(t)\rangle \tag{2}$$

Quantum mechanics then postulates that when a measurement of $\mathcal{O}$ is made, it will yield one of its eigenvalues o_i with probability $P(o_i) \propto |\langle\psi_i|\Psi\rangle|^2$, and the state of the system will change from $|\Psi(t)\rangle$ to $|\psi_i(t)\rangle$ as a result of the measurement. This assumption is known as the *Born's rule* and provides the link between the mathematical formalism of quantum theory expressed by eq.1 and the experimental results [3]. It represents the turning point where indeterminism enters fundamental physics, by identifying the square amplitude of the wavefunction as the probability distribution among the possibles observable $\mathcal{O}s$ in H. This means that if one performs a measurement on two equivalent systems with same initial conditions (e.g. temperature, pressure, number of particles etc..), we will obtain different results, according to the probability distribution identified by Born's statistical interpretation of the wavefunction. It is important to emphasize here, that there is nothing in the mathematical quantum prescription that implies, or even suggests, that the squared amplitude of the wavefunction should be used to define a probability [4]. Nonetheless, the resulting machinery works with spectacular accuracy and as such is responsible for practically all predictions of quantum physics.

The fundamental problem with this interpretation, is the physical significance associated to the measurement process, which suggests that making an observation actually affects a phenomenon, causing the wavefunction, which up to that point was described by the unitary evolution of the Schrodinger equation, to *collapse* onto the measured outcome [1]. This raises the question of what physically distinguishes interventions that are to count as *measurements*, capable of inducing a random and abrupt jump in the state of the system, from other interventions, which induce only the continuous, unitary and deterministic evolution of the SE [5]. If quantum theory is meant to be universal , it should be applicable, in principle, to all physical systems, including systems as large and complicated as an experimental apparatus. The assumptions that the wavefunction is a complete description of the system (A1) and evolves according to the linear dynamical SE (A2), are incompatible with the claim that each measurement has a definite result (C1) [4]. To show this, suppose we want to measure with a device M, the spin of a spin $\frac{1}{2}$ system S in a superposition of two different spins $|\Psi\rangle_S = \frac{1}{\sqrt{2}}(|\uparrow\rangle_S + |\downarrow\rangle_S)$.

Then, according to the unitary evolution of SE (A2), the composite system after the measurement will evolve into the superposition of two states: (1) M recording spin up and S being spin up and (2) M recording spin down and S being spin down [4].

$$|\Psi\rangle_{S\otimes M} = \frac{1}{\sqrt{2}}(|\uparrow\rangle_S|\uparrow\rangle_M + |\downarrow\rangle_S|\downarrow\rangle_M) \tag{3}$$

This superposed state which, according to A1, must specify every physical fact about the measuring device, clearly cannot yield a definite result for the instrument reading. Thus if A1 and A2 are correct, then C1 must be wrong. This is the so called *measurement problem*, a long-standing issue for interpreting the results of quantum mechanics, which emphasizes the relatively crude status of this "theory"[1], despite the extremely accurate predictions about macroscopic phenomena that is able to reproduce. To resolve this problem, we can distinguish mainly two approaches, which strictly relate to the assumptions A1 and A2 mentioned earlier:

1. Add additional structure to the mathematical formalism (denying A1). These are generally known as *hidden variables* theories and basically assume that far below the quantum level lie deterministic parameters, unseen to the observer, that control the observed quantum numbers [6]. The best known and developed among these, is the *pilot-wave* theory [7], originally proposed by de Broglie, in 1927 and then rediscovered by Bohm in 1952.

2. Modify the dynamics of the theory so that macroscopic superpositions do not occur (denying A2). These theories are still indeterministic and are often called *dynamical-collapse* theories, as they attempt to provide a cleanly formulated, microphysical theory which tells us exactly when the SE is violated and how this leads to the suppression of macroscopic superpositions [6]. The best-known theory of this type is the *GRW* theory [8], named after its creators, Ghirardi, Rimini, and Weber in 1986.

The above approaches were mentioned only for the sake of completeness and to provide a general prospective of state of quantum theory today. Nevertheless, in this paper, we will only explore a third approach for understanding the quantum formalism, which has been enthusiastically embraced by and increasing number of physicists in the last 3 decades, and has come to be known as the Many Worlds interpretation (MWI).

The MWI was originally proposed by Hugh Everett in 1957 [9], and simply stands on the insistence that A1 and A2 are the whole picture: all isolated systems evolve according to the SE and there is nothing else to be added to provide a complete, empirically adequate account of the world. In this view, the measurement

[1]As emphasized by Maudlin and Wallace respectively in [4] and [6], the mathematical quantum formalism combined with the reduction of state upon measurement, cannot be regarded as a scientific theory but rather as a mere recipe/algorithm which predicts all macroscopic phenomena.

dilemma becomes only apparent. The conclusion of an observation, such as that described above, is simply the uncollapsed state in eq.3, and these macroscopic quantum superpositions should just be thought as states of the world in which more than one macroscopically definite thing is happening at once [6]. Hence, macroscopic superpositions do not describe indefiniteness, they describe multiplicity. In terms of our spin experiment, after the observation is performed, rather than thinking of the observer with the measurement apparatus having evolved into a superposition of possible states, we should think of them as a multiplicity of states belonging to multiple worlds: one in which we measured the spin to be up and another in which we measured the spin to be down. The wave function never collapses, but rather a measurement, or any physical interaction between different objects, initiates a branching of the universe so that all the statistically possible results occur in each of these branches [4].

The Everett interpretation, as one would expect, given the radical and seemingly foolish conclusions it exhibits, has faced many objections throughout the decades, which here we summarize in two main categories: the *preferred basis* problem (P1) and the probability problem (P2).

P1 has to do with the the need of a justification for the fact that we don't perceive weird macroscopic superpositions in our daily experience of the world. This seems to imply that the branch emergence only occurs according to a preferred basis, namely the position basis. That said, we know that theoretically a quantum system can always be defined as a superposition with respect to some basis without changing its unitary evolution, so what makes the position representation so special? The answer to this important question is provided by the induced *entanglement*[2] from the interaction of the macroscopic objects with the environment [6]. This process is called *decoherence*, and it's what causes the wave function to branch into multiple worlds, by rapidly destroying macro-superpositions as far as the inside view is concerned[3] [11]. In relation to our spin measurements, the fact they are entangled with the different states of the detector and environment means that the two possible outcomes from the $S \otimes M$ wave function can no longer interfere with each other, hence they are essentially part of separate worlds. From an inside prospective, this decoherence machanism is completely indistinguishable from the wavefunction collapse, which is indeed only apparent [11].

In regards to P2, the issue lies on the deterministic nature of the MWI which seems to make any talk of probability meaningless in this context. In fact, in MWI, if we know the wave function of the Universe at one

[2]Entanglement is an observed quantum mechanical phenomenon in which the states of two or more objects have to be described with reference to each other, even if spatially separated. In entanglement, one constituent cannot be fully described without considering the other, which results in a form of non-locality that is alien to classical physics [5].

[3]This mechanism is now well-understood and rather uncontroversial. Essentially, what we get is that the position basis gets singled out by the dynamics because it is the only basis in which the field equations of physics are local [10].

moment in time[4], then we can precisely predict what it's going to be at any other time, according to the SE; so how come we recover the reality of our observations, where measurements in the microscopic scale seem irreducibly random? On a more fundamental level, as emphasized by Maudlin in [4], how can we even define a measure of probability if, according to MWI, there are no alternative possibilities since all the branches actually exist? To respond to these questions, I believe is important to recognize, as Wallace asserts in [6], that all the issues with probability seem to arise more from the intrinsic philosophical difficulties of defining any measure, rather than from its application to the MWI. The MWI is able to predict the apparent randomness relative to the inside viewpoint of the branch, by simply considering the weights attached to the squared amplitudes that distinguish each the branches from one other [9]. The basic idea is that, from the inside perspective, after any observation is performed, the observers are subject to *self-locating uncertainty*, since they don't know which branch they're on, given the rather instantaneous splitting caused by decoherence [11]. This ignorance allows us to talk about probabilities and assign a credence to being on one branch or the other. What seems the most reasonable thing to do is to use the structure of quantum mechanics itself to pick the preferred set of credences, which would then correspond exactly to those one would get from the Born's rule. Surely, as Maudlin points out, there is nothing mathematically that forbids us from assigning a different rules to determine our credences [4], but this once again seems to be a more general problem that probability theory needs to face as a whole. As Sean Carroll lucidly explains in [11], if MWI is correct, we are going to find ourselves in situations of self-locating uncertainty whether we like it or not, and, in a goal to achieve the best scientific understanding of the world, we will have to necessarily assign credences. Since, the structure of the theory points to one particular way to assign such credences, which agrees with our experimental data, then the only reasonable thing to do is to adopt this way.

Despite the reasonably satisfactory answers provided by the advocates of the MWI to its major objections, I still don't think we can ascribe any physical significance to this interpretation. In fact, it relies on an important assumption, that does not naturally emerge from the mathematical quantum formalism, which is that to interpret the superpositions of quantum states as a multiplicity. Coming back to our original example of the spin measurement, before the observation the system S in a superposition of two different spins, then once we perform a measurement with the device M, the whole system (observer + measuring device +spin) becomes a superposition of the two possible outcomes. There is nowhere in the theory that implies that we have multiple disjoint worlds, at its core what the quantum formalism truly describes is just one *superimposed* world. One may say this is a rather funny world, clearly not a world we see, as we never experience macroscopic

[4]here by Universe, we truly mean the collection of all the parallel and disjoint worlds that keep on arising from the decoherence, following the interaction between quantum systems.

superpositions of any kind.

What the advocates of the MWI always emphasize is that the Everett's interpretation is the only theory that follows the quantum formalism rigorously. If we interpret the superpositions of different states as a multiplicity, then they are correct, as thoroughly shown in this paper, MWI is just what the quantum mechanics formalism entails, as expressed by its unitary evolution of the SE. As recognized by Sean Carroll himself, the price we pay for this vastly increased elegance of theoretical formalism is that the theory describes many copies of the universe, each slightly different, and truly real in some sense [11]. I stand for the fact that this cost is not worth the price. It seems to me very arbitrary to just accept a unitary evolving state vector such $|\Psi\rangle$ as describing reality as perceived by us. To conclude, we may use Feynman words: "if you think you understand quantum mechanics, then you don't"[5]. The crude reality is that nearly 100 years after the theory's development, there is still no consensus in the scientific community regarding the interpretation of the theory's building blocks, with the majority either uninterested in the question itself (those who still accept the inconsistent picture of the wavefunction collapse), or denying any issue, by accepting the whole theory and its extravagant consequences as true (the MWI adamants).

Word Count ~ 2350

[5] A Youtube video of Feynman saying exactly this can be found at this link.

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