Foundations of Physics
https://doi.org/10.1007/s10701-020-00360-6

Quantum Mechanics and Its Interpretations: A Defense of the Quantum Principles

Sébastien Poinat[1]

Received: 4 June 2020 / Accepted: 11 July 2020

Abstract

One of the most striking features of the epistemological situation of Quantum Mechanics is the number of interpretations and the many schools of thought, with no consensus on the way to understand the theory. In this article, I introduce a distinction between orthodox interpretations and heterodox interpretations of Quantum Mechanics: the orthodox interpretations preserve all the quantum principles while the heterodox interpretations replace at least one of them. Then, I argue that we have strong empirical and epistemological reasons to prefer orthodox interpretations to heterodox interpretations. The first argument is that all the experiments on the foundations of Quantum Mechanics give a high degree of corroboration to the quantum principles and, consequently, to the orthodox interpretations. The second argument is that the scientific progress needs a consensus: this consensus is impossible with the heterodox interpretations, while it is possible with the orthodox interpretations. Giving the preference to the orthodox interpretations is a reasonable position which could preserve both a consensus on quantum principles and a plurality of views on Quantum Mechanics.

Keywords Quantum mechanics · Interpretations · Quantum principles · Orthodox interpretations · Heterodox interpretations

1 Introduction

Throughout its 90 years of life Quantum Mechanics has given birth to several versions that are usually called “interpretations of Quantum Mechanics”: Bohr’s interpretation, De Broglie’s interpretation, Bohm’s interpretation (Bohm, Hiley), Everett’s interpretation and its variants (Everett, DeWitt and Graham, Saunders, Wallace), the many-minds interpretations (Albert and Loewer, Lockwood), the

---

✉ Sébastien Poinat
sebastien.poinat@univ-cotedazur.fr

[1] Université Côte d’Azur - Centre de Recherches en Histoire des Idées, 98 Boulevard Edouard Herriot, 06000 Nice, France

modal interpretations (Healey, van Fraassen, Dieks, Bub), the interpretations based on decoherence (Joos, Zeh, Zurek), the Itaca interpretation (Mermin), the information interpretation (Bruckner, Zeilinger), Popper's interpretation, the consistent histories interpretations (Griffiths, Gell-Mann and Hartle, Omnès), the objective collapse interpretation (Ghirardhi, Rimini and Weber), the statistical interpretation (Ballentine), Rovelli's interpretation, the pragmatist interpretation (Bächtold), the Qbist interpretation (Fuchs)...

This list is not exhaustive but is sufficient to show how large the number of different versions of Quantum Mechanics has become. The state of the discussion changed over the years: some interpretations are not judged convincing anymore, while some others are actively discussed. Due to the collective discussion about the best interpretation, some progress have been made. But there is still no consensus on the way to understand the theory and the epistemological landscape remains composed of many schools of thought.

What can we do to produce more consensus?[1] Of course, those who defend one particular interpretation must formulate it in the clearest way and try to convince everybody that it is the best interpretation.

In this article, I don't defend one particular interpretation but rather a group of interpretations. I introduce a distinction (Sect. 2) between the orthodox interpretations, which preserve the four quantum principles of the Standard Quantum Mechanics, and the heterodox interpretations, which replace at least one quantum principle. I try to show that we have empirical reasons (Sect. 3.1) and epistemological reasons (Sect. 3.2) to prefer orthodox interpretations to heterodox interpretations. Giving the preference to the orthodox interpretations is a reasonable position which could preserve both a consensus on quantum principles and a plurality of views on Quantum Mechanics.

2 Orthodox Interpretations and Heterodox Interpretations

Quantum Mechanics is a theory with a mathematical formalism, whose mathematical meaning is now well understood. On the contrary, the best way to interprete physically the mathematical formula has been intensively discussed since the birth of Quantum Mechanics. Is the wave function real? Does the state vector represent the physical state of the system? Does Quantum Mechanics say something about a physical reality independent of us? And so on. By definition, an interpretation of a theory tries to give a physical meaning to a mathematical formalism and this is the first task of any interpretation of Quantum Mechanics.

But an interpretation of Quantum Mechanics must go further because the mathematical formalism of Quantum Mechanics contains an internal contradiction, called "the Measurement Problem", and any interpretation must also try to solve this problem. Because solving an internal contradiction requires to change the mathematical

---

[1] For more details about the importance of the consensus, see Sect. 3.2

formalism, the interpretations of Quantum Mechanics is a way to modify the quantum mathematical formalism and to give a physical meaning to it.

The main goal in this section is to show that is possible to classify the interpretations of Quantum Mechanics according to the way they change the mathematical formalism. In order to do that, Sect. 2.1 will first recall, in a very synthetical way, the mathematical formalism of Quantum Mechanics and Sect. 2.2 will expose the Measurement Problem. Then Sect. 2.3 will identify three conditions that any solution to the Measurement Problem should verify. From these three conditions, Sect. 2.4 will show that we can identify two strategies to solve the Measurement Problem and will introduce a distinction between orthodox and heterodox interpretations.

2.1 The Four Principles of Standard Quantum Mechanics

The Principles of Quantum Mechanics appeared at the end of the 1920's and they have not changed since that period. We can formulate them in a simple manner:

- Principle 1 (P_1): the space of all possible mathematical states of a quantum system S is represented by a complex Hilbert space H and the mathematical state of S is represented by a state vector $|\Psi\rangle$ belonging to H. If the system S is composed of two systems S_1 and S_2, the space of all its possible states is represented by the tensor product $H_1 \otimes H_2$ and its state by $|\Psi\rangle_1 \otimes |\Psi\rangle_2$.
- Principle 2 (P_2): any physical quantity, attached to the quantum system, is represented by a self-adjoint operator A on H. These are usually called *observables* of the system. The set of different possible values for the measurement of an observable A is its spectrum $\sigma(A)$.
- Principle 3 (P_3): the only possible numerical outcome for the measurement of A is an element of its spectrum $\sigma(A)$ and the measurement result is generally random. If a_k and $|k\rangle$ are the eigenvalues and the eigenvectors of A, and if $|\Psi\rangle$ is the state vector of a given system, the probability of obtaining a_k as the outcome of the measurement of A is $P(a_k) = |\langle k|\Psi\rangle|^2$ (this is the Born's rule). If the outcome of the measurement is a_k, the state vector of the system after the measurement is equal to $|k\rangle$ (this last assertion is usually called the "collapse of the wave function"[2]).
- Principle 4 (P_4): the evolution of the state vector $|\Psi\rangle$ of a closed system S is given by Schrödinger's equation: $i\hbar\frac{d|\Psi(t)\rangle}{dt} = H(t)|\Psi(t)\rangle$, where $H(t)$ is the Hamiltonien operator (which represents the energy of the system).

As we said, these principles define the heart of the theory (for comments on the principles, see [23]). They could already be found in Dirac [8] in 1930 or in von Neumann [35] in 1932, the two first complete formulations of the quantum theory, even if there were not presented exactly as we did here. Despite the debate about

---

[2] The collapse of the wave function was historically seen as one of the quantum principles. It is now a matter of debate to know if we must keep it inside the area of the quantum principles.

how we should understand Quantum Mechanics, these principles hadn't changed since the birth of Quantum Mechanics.

2.2 The Measurement Problem

The principal root of the debate between the different ways of understanding Quantum Mechanics is the famous Measurement Problem. This problem occurs because we have two ways of describing a quantum measurement. Synthetically it goes as follows.

2.2.1 The Collapse of the Wave Function

The first way to describe a measurement is based on Principle 3. For example, let us suppose that we measure the spin along direction Ox of a spin $\frac{1}{2}$ system and that the eigenvectors of the spin along Ox are $|+\rangle$ and $|-\rangle$. Before the measurement we have

$$|\psi\rangle_{init} = \alpha|+\rangle + \beta|-\rangle \tag{1}$$

(with α and β two complex numbers such that $|\alpha|^2 + |\beta|^2 = 1$)

If α or β is equal to zero, the state is an eigenstate of the spin along Ox. Otherwise, it is a superposition of states (we will explain quantum superpositions in more details in Sect. 3.1). But in the two cases (an eigenstate or a superposition of states), the result of the measurement is either "+" (with a probability equal to $|\alpha|^2$), either "-"(with a probability equal to $|\beta|^2$) according to Born's rule. After the measurement, the state vector is projected into one of the eigenvectors of the observable (the physical quantity) that is measured. Thus, if the result is "+", we have:

$$|\psi\rangle_{final} = |+\rangle \tag{2}$$

As we will see now, this result is in contradiction with a second way to describe a quantum measurement, based on Principle 4.

2.2.2 The Apparatus as a Quantum System

The second way to describe a quantum measurement considers the apparatus A as a quantum system. Like the other physical systems, we should be able (at least in theory) to assign a state vector $|\Sigma\rangle$ to A. We suppose that $|\Sigma\rangle$ belongs to the Hilbert State H_2. We note $|\Sigma\rangle_+$ (resp. $|\Sigma\rangle_-$) the state vector of A when the outcome is "+" (resp. "$-$").

According to Principle 1, the state vector $|\Psi\rangle$ of the global system S-A belongs to the Hilbert State $H_1 \otimes H_2$. Before the measurement, it can be written like this:

$$|\Psi\rangle_{init} = |\psi_{init}\rangle \otimes |\Sigma\rangle_{init} \tag{3}$$

According to Principle 4, the interaction between the two physical systems during the measurement leads to an entangled state for the global system. From 3, we have:

$$|\Psi\rangle_{final} = \alpha|+\rangle \otimes |\Sigma\rangle_+ + \beta|-\rangle \otimes |\Sigma\rangle_- \tag{4}$$

The entangled form of the vector is such that it is now impossible to factorize $|\Psi\rangle$ and to assign a state vector to S. The only thing we can say is that the state of the global system $S - A$ is an entangled state. The measurement does not have a result.

If we compare the two descriptions of a quantum measurement, we see that there is a contradiction between 2 and 4. This contradiction is what I call here the "Measurement Problem".

2.3 Three Conditions That Any Solution of the Measurement Problem Must Verify

As we saw, each quantum interpretation can be seen as a proposition to solve the Measurement Problem and to give a physical meaning to the mathematical formalism. Here we won't examine all the interpretations and their different ways to try to solve the Measurement Problem. I will make a general analysis and identify three conditions that any solution to the Measurement Problem should verify.

In order to identify these two main strategies, we will start with a purely logical examination of the situation. As we said, the Measurement Problem comes from the fact that the four quantum principles lead to two descriptions of a quantum measurement which are contradictory. In Sect. 2.1 we noted P_1, P_2, P_3 and P_4 the four quantum principles. Let us note $S = \{P_1; P_2; P_3; P_4\}$ the set of the quantum principles. In Sect. 2.2, we saw that the Measurement Problem is a contradiction between two descriptions of a quantum Measurement: the first one uses P_3 and leads to equation 2, while the second one uses P_4 and leads to equation 4.

Thus we have:

$$\begin{cases} P_1 \wedge P_2 \wedge P_3 \Rightarrow \ 2 \\ P_1 \wedge P_2 \wedge P_4 \Rightarrow \ 4 \\ 2 \wedge \ 4 \Rightarrow \perp \end{cases} \tag{5}$$

where $\wedge$, $\Rightarrow$ and $\perp$ are the symbols of the conjunction, the relation of implication and the contradiction.

Each interpretation of Quantum Mechanics will thus propose a new set of principles. We note S' this new set and P'_i the principles of S'. If N is the number of principles of S', we have $S' = \{P'_1; P'_2; \ldots; P'_N\}$. Let us now write the three conditions that S' must verify.

First of all, this new set S' must not imply any contradiction:

$$P'_1 \wedge P'_2 \wedge \ldots \wedge P'_N \nRightarrow \perp \tag{6}$$

A second condition is that the new principles must be in a good agreement with the empirical results of all the quantum experiments that have been done up to now. This is the case with the initial set: up to now, Standard Quantum Mechanics has never been in contradiction with any experimental result. Let us suppose that we can express each experimental result by a proposition. We note R_i the proposition of the ith experimental result. Thus we want this relation to be verified:

$$\forall i, (P'_1 \wedge P'_2 \wedge \ldots \wedge P'_N) \Rightarrow R_i \tag{7}$$

The third condition concerns the resolution of the Measurement Problem. There is a difference between equation 2 and equation 4 because equation 2 corresponds to what we can actually observe, while equation 4 does not. Thus in order to solve the contradiction, we must keep equation 2 and avoid equation 4. In other words, we want S' to imply 2, but not 4:

$$\begin{cases} P'_1 \wedge P'_2 \wedge \ldots \wedge P'_N \Rightarrow 2 \\ P'_1 \wedge P'_2 \wedge \ldots \wedge P'_N \nRightarrow 4 \end{cases} \tag{8}$$

This third condition (8) is implied by the condition (6) and the condition (7) but it is useful to formulate this condition as if it was a new condition.

Thus any interpretation of Quantum Mechanics must propose a new set S' of N principles that verifies condition (6), condition (7), and condition (8).

2.4 The Two Strategies to Interpret Quantum Mechanics

How can we generate a new set S' of principles that verify the three conditions 6, 7 and 8? In order to list the different possibilities, we can start from S and think about the different basic operations that we can operate on S. These basic operations are:

- adding one or several new principles (operation O_1);
- taking off one or several principles (operation O_2);
- introducing some restrictions on the domain of validity of one or several principles (operation O_3).

Let us explain operation O_3. In the Standard Quantum Mechanics, the quantum principles are supposed to be universal: no explicit restriction on their domains of validity is mentioned. But to generate a new quantum version, we can add a restriction to the domain of validity of a principle (for example we could say that the Schrödinger equation is true only for microscopical systems). If we note D_4 the domain of validity of P_4, the new set will be $S' = \{P_1; P_2; P_3; P_4 \wedge D_4\}$.

Let us explain how a new set of principles can be generated by a combination of these three operations. For example, we can use O_2 and O_1 (in this order or in the reverse order, it doesn't matter): we take off one principle to S and add a new principle, and generate a new set of this type $S' = \{P_1; P_2; P_3; P'_4\}$, or of this type $S' = \{P_1; P_2; P_3; P'_4; P'_5\}$. All the solutions of this kind can be gathered in a specific category: the category of all the solutions that use operations O_1 and O_2 to generate the new set of principles. In the same manner, we can gather all the possible solutions in different categories according to the operations they use to generate the new set of principles.

How many categories do we have? At a pure logical level, the number of categories of solutions is 7 (3 categories of solutions generated by the use of only one operation, 3 categories of solutions generated by a combination of exactly two operations, 1 category of solutions generated by a combinaison of the three operations). But some of the combinations don't verify the three previous conditions 6, 7 and 8. Thus a set produced only by the operation O_1 is not a solution because the condition 6 would not be verified. A set of principles produced only by the operation O_2, and a set produced only by the operations O_2 and O_3, are not acceptable neither because they would not verify the condition 7.

Finally any solution to the Measurement Problem belongs to one of these four categories:

1. the category of solutions that use O_3 to generate the new set;
2. the category of solutions that use O_3 and O_1 to generate the new set;
3. the category of solutions that use O_1 and O_2 to generate the new set;
4. the category of solutions that use O_1, O_2 and O_3 to generate the new set.

The two first categories of solutions don't use operation O_2: they don't take off any quantum principle. Thus even if they can be quite different from each others, all these solutions have something in common that is very important : they keep the four quantum principles. Indeed examples of solutions of these categories are: $S' = \{P_1; P_2; P_3; P_4 \wedge C_4\}$, or $S' = \{P_1; P_2; P_3 \wedge C_3; P_4; P'_5\}$. With these solutions, S' contains all the quantum principles, with restrictions of the domains of validity for some of them, and maybe some new principles in addition. It defines what we can identify as the first strategy to solve the Measurement Problem. Because they keep the four quantum principles, these interpretations are not very far away from Standard Quantum Mechanics and we can call them "the orthodox interpretations of Quantum Mechanics".

The situation is different with the two last categories of solutions: because these categories use operation O_2, the new sets of principles don't keep the four quantum principles. More precisely, all the solutions of these categories combine O_1 and O_2: at least one new principle is substituted to at least one quantum principle. Examples of these categories are $S' = \{P_1; P_2; P_3; P'_4\}$, $S' = \{P_1; P_2; P_3; P'_4; P'_5\}$, or $S' = \{P_1; P_2; P_3 \wedge D_3; P'_4; P'_5\}$. The key feature is that the new sets of principles S' abandon at least one quantum principle. It defines what we can identify as the second strategy to solve the Measurement Problem and the solutions of this type can be called "the heterodox interpretations of Quantum Mechanics".

Let us resume: any interpretation of Quantum Mechanics must propose a new set of principles that solves the Measurement Problem. Thus the new set of principles must verify the three conditions 6, 7 and 8. Any such new set of principles can be described from three basic operations (O_1, O_2 and O_3) and we can define four categories of solutions, each category being defined according to the operations that is used to generate the new set of principles. Finally we define two meta-categories of solutions: the orthodox interpretations are the solutions that keep the four quantum principles, the heterodox interpretations are the solutions that substitute at least one new principle to at least one quantum principle.

Appendix gives four examples of orthodox interpretations (Bohr's interpretation, the propensionist interpretation, Rovelli's interpretation, and the pragmatist interpretation) and three examples of heterodox interpretations (Bohm's interpretation, Everett's interpretation, and the GRW interpretation).

3 Against the Heterodox Interpretations of Quantum Mechanics

In this section I give two arguments against the heterodox interpretations of Quantum Mechanics and in favor of the orthodox interpretations of Quantum Mechanics.

3.1 First Argument: *Gedanken Experiments* and Quantum Principles

Since the birth of Quantum Mechanics, fundamental aspects of the theory have been discussed. A way to do it consists in using *Gedanken experiments* (or thought experiments) and many such experiments were proposed at the very beginning of Quantum Mechanics: the microscope of Heisenberg to explain his relations in 1927, the experiment with the cat by Schrödinger in 1935, all the devices invented by Einstein and Bohr to feed their discussion about Quantum Mechanics. At the middle of last century, Erwin Schrödinger said in [30] that manipulating an isolated atom would remain forever impossible: “We never experiment with just one electron or atom or (small) molecule. In thought-experiments we sometimes assume that we do; this invariably entails ridiculous consequences”. The situation has dramatically changed because a lot of these *Gedanken experiments* became real experiments. Thus we can now ask the nature to help us in our debates on foundations of Quantum Mechanics. As explained by Serge Haroche and Jean-Michel Raimond in [16], these experiments help us to understand Quantum Mechanics and its basic concepts:

> Most of the thought experiments realized recently are made of simple basic elements. Inside a confined region of space [...], a few atoms or photons evolve, largely impervious to what happens in the outside world. On this simple stage, the laws of the game are the quantum postulates. State superpositions, quantum interference and entanglement are directly displayed, illustrating as clearly as can be the quantum concepts. (Haroche and Raimond 2006)

A lot of work has been done [10, 16, 19, 36] and it is impossible to list all the experiments done in this field, but we can list several categories:

- experiments on single microscopic system (see experiments with one photon in [3, 14, 28])
- experiments on quantum interferences (like Young double-slit experiment) and complementarity of wave and particle aspects (see Quantum interference with molecules containing up to 430 atoms in [12]);

- experimental creation of superposition of states to explore the boundary between quantum mechanics and classical physics (see the generation of bigger and bigger Schrödinger cats in [11, 21, 33];
- photonic experiments to explore entanglement and nonseparability (see all the experiments on EPR inequalities: the historical experiment by Aspect in [1], and some more recent ones in [2, 17, 20, 22, 31, 34])
- experiments on Born's rule (see for example [32])

Up to now, none of these real experiments concerning the foundation of Quantum Mechanics refuted the quantum principles. On the contrary the results correspond to the quantum predictions and these experiments are corroborations of the principles of Quantum Mechanics. It is not possible to analyse all of them but we can take one experiment as representative of the rest and show how an experimental result can corroborate foundations of Quantum Mechanics. In order to do that, I analyse the experiment made by Guerlin and al. in 2007 [15].

This experiment is based on the superposition of states and we first have to explain this kind of quantum states. In order to do it, let us suppose that we can measure a physical quantity A on a system S and let us call $|e_1\rangle, |e_2\rangle, |e_3\rangle \dots$ the different eigenvectors associated to the results $r_1, r_2, r_3 \dots$ of the measurement of A. If S is in state $|e_i\rangle$ the result of the measurement of A will be (with full certainty) r_i. According to Principle 1, Quantum Mechanics allows states that are linear combinaisons of $|e_1\rangle, |e_2\rangle, |e_3\rangle \dots$. Thus $\Sigma_i c_i |e_i\rangle$ (with c_i complex numbers and $\Sigma |c_i|^2 = 1$) are quantum possible states. These kind of states are precisely a superposition of states. Because they correspond to a mathematical property of Hilbert Spaces, the fact that Quantum Mechanics allows these kind of physical states is just a consequence of Principle 1. While these states are at the heart of Quantum Mechanics, they do not exist in classical physics and if we measure A on S, according to Principle 3, we will obtain only one result among all the possible results r_i. At a macroscopic level, we do not observe quantum superpositions. This situation is analyzed and discussed by Schrödinger [29] with the famous cat. At a macroscopic level a cat is "dead" or "alive" and Schrödinger imagines it in a linear combinaison of "dead" and "alive". The question is thus: because this linear combinaison of "dead" and "alive" cat seems to be a consequence of Quantum Mechanics while we have never seen a real cat in this kind of state, does it show Quantum Mechanics is wrong? If not, for what reason this kind of state does not appear at macroscopic level?

In 2007 Guerlin and al. made an experiment that shows the generation of an optical Schrödinger cat and the progressive collapse of its state. In this experiment, the cat is the light (the electromagnetic field) in a cavity and the two states of the cat ("alive" and "dead") become eight quantum states: zero photon in the cavity ($|O\rangle$), or one photon ($|1\rangle$), or two ($|2\rangle$),...up to seven photons ($|7\rangle$) in the cavity. We can't directly observe the superposition (if we measure the photon number, we destroy the superposition and find an integer) but we can try to observe one of its experimental consequences and, from it, deduce that we are indirectly observing a superposition of states. Without entering precise physical aspects of this experiment, we can say that the number of photons in the cavity is entangled with a two-level atom. A first atom crosses the cavity, and becomes entangled with the light. Then, after giving a pulse to the atom, a measurement of the state of the atom is made. From the result and by using Bayes' rule of conditional probability, one can compute the probability distribution of the photon number. Because several photon numbers in the cavity can lead to the same result of the measurement of the state of the atom, we cannot deduce *one* photon number: we can only compute the probability of *several* photon numbers from 0 to 7. In other words, the information about the photon number is only partial, this is why the measurement of the state of one atom doesn't reduce the quantum state of the light to one eigenstate of photon number.

An eigenstate of the photon number in the cavity corresponds to a distribution with one peak (the distribution is equal to zero for the other values). A superposed state corresponds to a distribution with at least two picks. At the beginning of the experiment, the distribution is supposed to be flat, corresponding to a quantum superposition where each possible state has the same weight. Progressively, after the measurement of few atoms crossing the cavity, some values of photon number begin to disappear (the distribution function is equal to zero for them) and several peaks begin to appear. Then, more and more values of photon number disappear and less and less peaks manage to last. At the end, the distribution converges to only one peak, which corresponds to a photon number in the cavity equal to one integer. This progressive convergence of the function can be seen as the experimental manifestation of the progressive collapse of state function due to measurement.

The experiment contains another very interesting result. In order to reconstruct the photon number statistics, the field was prepared in the same coherent state 2 000 times and the previous experimental determination of the photon number was applied each time. 2 000 photon numbers were then obtained, with an experimental average equal to 3.82. A small part of the photon numbers (23 %) does not correspond to an integer (due to sequences that have not fully collapsed or that have been interrupted by field decay) but the rest of the photon numbers forms an histogram with clear peaks at integers. Furthermore the histogram of integer values can be fit to a Poisson law centered at 3.46. This distribution corresponds to what can be expected for a coherent field with an initial mean equal to 3.82. This histogram can be seen as the experimental manifestation of the Born's rule. As the authors of the experiments write, "the near-perfect agreement of the fit with the experiment provides a direct verification of the quantum postulate about the probabilities of measurement outcomes".[3]

In this experiment everything happens as predicted by Quantum Mechanics:

1. the experiment produces "Schrödinger cats" whose behavior is what Principle I says about system in superposition of states.
2. the experiment shows that the measurement of the photon number can lead to several results and that the statistical distribution is a Poisson law. This is what Principle II says.

---

[3] A third result of this experiment illustrates another fundamental feature of Quantum Mechanics: the possibility to repeat measurements.

3. the measurement of the photon number can be made in a very progressive way and the progressive vanishing of the superposition is observed. The collapse of the state function is what is asserted by Principle III and the experiment can be seen as a spectacular corroboration of Principle III.

This experiment is a representative example of experiments on foundations of Quantum Mechanics. It illustrates what we can learn in general from all these experiments:

- While they are not empirical falsifications of the heterodox interpretations, the experiments on foundations of Quantum Mechanics are strong corroborations of the quantum principles and, consequently, of the orthodox interpretations. The notion of degree of corroboration was introduced by Popper in [24]: the degree of corroboration is "'nothing but a measure of the degree to which a hypothesis *h* has been tested, and of the degree to which it has stood up to tests". From the quantum principles, one can derive direct consequences that are in agreement with what is observed through these experiments. That's why we can say that the degree of corroboration of the quantum principles is rather high now, and that experiments on foundations of Quantum Mechanics give to us some strong empirical reasons to prefer orthodox interpretations (which are based on quantum principles) to heterodox interpretations (which refute at least one of them).
- Of course, the question about the domain of validity of each quantum principle remains open: the experiments are empirical tests in narrow conditions, and from them we can't know exactly the extension of physical conditions under which the quantum principles are corroborated. As we seen previously, orthodox interpretations keep the quantum principles but they differ from each other about the domains of validity of quantum principles. This question is still open and these experiments can't arbitrate between different orthodox interpretations.

3.2 Second Argument: The Plurality of Heterodox Interpretations *versus* Scientific Consensus

My second argument tries to show that the strategy of orthodox interpretation allows the consensus which is required for scientific progress, while the strategy of heterodox interpretation does not. This argument is based on the description of scientific activity by Thomas Kuhn in his article "The Essential Tension. Tradition and Innovation in Scientific Research" written in 1959 [18]. Kuhn explains that history of science shows episodes, called "revolutionary (or extraordinary) phases" in which a scientific community abandons its way of regarding the world and of pursuing science (its "paradigm", as he will call it later). The community changes it in favor of another way of regarding the world and of pursuing science, a new theory becomes dominant and the old theory is abandoned. Revolutionary phases are very important in the development of science and their role in scientific progress is usually emphasized. But Kuhn insists on the role of the other phases: the "normal"' phases of scientific development. During these phases, scientists try to solve puzzles: how to bring existing theory and existing observation into closer agreement, how to extend the existing theory to areas that is expected to cover but in which it has never before been tried, and how to collect more concrete data required for the application and extension of existing theory. These kinds of works are very important for the development of science and for its progress. But they need a strong commitment by the relevant scientific community to their shared theoretical beliefs, values, instruments and techniques. As Kuhn writes:

> These are normal research projects in the basis sciences, and they illustrate the sorts of work on which all scientists, even the greatest, spend most of their professional lives and on which many spend all. [...] Only if the validity of the contemporary scientific tradition is assumed do these problems make such theoretical or any practical sense. [...] Under normal conditions the research scientist is not an innovator but a solver of puzzles, and the puzzles upon which he concentrates are just those which he believes can be both stated and solved within the existing scientific tradition. (Kuhn 1959)

Scientific community has empirical and theoretical tools to solve many scientific problems and this is why normal science is also an important phase of scientific progress. On the contrary, when there is no settled consensus, scientific activity is not at the same level of success. Kuhn take the historical example of physical optics. Before the eighteen century and Newton's *Opticks*, there was no consensus and no scientific progress:

> From remote antiquity until the end of the seventeenth century there was no single set of paradigms for the study of physical optics. Instead, many men advanced a large number of different views about the nature of light. Some of the views found few adherents, but a number of them gave rise to continuing schools of optical thought. [...] One can scarcely escape the impression that, during the period characterized by this more liberal educational practice, physical optics made very little progress. (Kuhn 1959)

My argument is that the plurality of heterodox interpretations could drive us to this kind of situation and could slow down scientific progress in the domain of Quantum Mechanics. Of course, no heterodox interpretation taken isolated is a threat to the scientific progress: the argument concerns the heterodox interpretations taken together, as a group.

As we saw in the previous section, heterodox interpretations are based on new sets of principles of the form: $S' = \{P'_1; P'_2; \ldots; P'_N\}$. Even if an heterodox interpretation can keep unchanged some of the quantum principles, there is no reason why all the heterodox interpretations will keep the same quantum principles. Thus they will not have a common core: heterodox interpretations are contradictory and a consensus among them is not possible. Scientific activity risks to be as optical physics before Newton's *Optiks*: a scientific landscape composed by several schools, each defending its own approach, without the settled consensus required by scientific progress in normal phase of scientific development.

Indeed several aspects of the scientific activity could be impacted by this lack of consensus. First, it would bring strong difficulties for the discussion about some philosophical or theoretical consequences of Quantum Mechanics. For example, physical processes in Bohm's interpretation (at least in some variants of Bohm's interpretation) are intrinsically deterministic, while they are not in GRW's interpretation: how could we have a discussion on quantum randomness if we can choose any of the two versions? In Everett's interpretation, physical interactions are local, while they are not in Bohm's interpretation. How can we discuss about locality? Without a consensus among the interpretations, the philosophical or theoretical discussions are interpretation-dependent.

Secondly, we would have problems with scientific communication. If all the interpretations of a theory are acceptable, which one should we choose to write the papers? If everyone can choose its own version (with its ontology, its laws, its hypothesis), how can we understand each other? There is a strong need to have one version to be easily understood by everyone, and not only by those who know the particular version adopted in a given paper.

Thirdly, the plurality of heterodox interpretations is also a problem for teaching activities. Which version of Quantum Mechanics should a physicist teach to his students? If he teaches his favorite version, he will just transfer his philosophical tastes to his students. Then, his students will be trained with some particular version, while other students will be trained with another version. They will have strong difficulties to work together after being graduated. To avoid these problems, we should prefer the kind of education that is currently adopted in natural sciences. As Kuhn explains in [18], education in natural sciences is "a dogmatic initiation in a pre-established tradition that the student is not required to evaluate" in the sense that scientific community chooses one tradition and teaches this tradition to the students. The students are not exposed to all the possibilities, and this kind of education allows further scientific progress in normal phase and in revolutionary phase: "this technique of exclusive exposure to a rigid tradition has been immensely productive of the most consequential sorts of innovations". I think that we had better to teach the quantum principles, which are our tradition in Quantum domain.

Thus the lack of consensus produced by the heterodox interpretations (as a group) will appear in several domains: discussions on philosophical and theoretical aspects of Quantum Mechanics, scientific communication, teaching activities. We risk to be in the problematic situation described by Thomas Kuhn: a science in a normal phase without the consensus required by the scientific progress.

Contrary to the plurality of heterodox interpretations, the plurality of orthodox interpretations is not a threat to scientific progress because it maintains a common core: the quantum principles. As we saw in the previous section, orthodox interpretations are of the form: $S' = \left\{P_1 \wedge C_1; P_2 \wedge C_2; P_3 \wedge C_3; P_4 \wedge C_4\right\}$. In all the orthodox interpretations, we find the four quantum principles (while the C_i are different from one orthodox interpretation to another) and a consensus on them is still possible. Thus we can base our discussions on the philosophical and theoretical consequences of quantum principles, we can teach them in courses and use them in scientific papers. The differences between orthodox interpretations are very small compared to what they have in common, this is why the plurality of orthodox interpretations is compatible with the need of a large consensus (while the plurality of heterodox interpretations is not).

Fortunately scientific community shares the same paradigm (in Kuhn's sense) given by the standard version. With its four principles, it is the version that is used by scientific community to formulate philosophical or theoretical questions about Quantum Mechanics, it is the version used in scientific papers to communicate with other physicists, and it is the version that is taught in almost every textbook on Quantum Mechanics and in almost every courses in physics. Thus, the standard version has a priviledged position inside physics. Giving the preference to the orthodox interpretations would enforce this privileged position and the consensus needed by scientific progress for science in normal phase.

4 Conclusion

The epistemological landscape of Quantum Mechanics is composed of many schools of thought, with no consensus on the way to understand the theory. In this article, I defend that it is possible to find a reasonable stance that can both produce a consensus and preserve a plurality of views. I propose to classify quantum interpretations in two categories, the orthodox interpretations and the heterodox interpretations. I argue that we have strong reasons, both empirical and epistemological, to prefer the orthodox interpretations to the heterodox interpretations.

The distinction between orthodox and heterodox interpretations is based on a choice between two mathematical options to solve the Measurement Problem. This distinction is not based on a philosophical choice. In particular, it is not based on the opposition between scientific realism and scientific antirealism. This can be understood by noticing that some orthodox interpretations are realist, while some other are anti-realist[4]. When someone gives his preference to one particular interpretation, he has to choose between realism and anti-realism but at the steep of the orthodox/heterodox distinction, we don't have to make any realist or antirealist commitment. For this reason, this position can be seen as a balanced position between the need of consensus on the quantum principles and the need of plurality of views on Quantum Mechanics and on the philosophical issues associated to scientist theories.

Acknowledgements A first version of this paper was carefully read by Michel Le Bellac, who made a lot of very important remarks. I would like to thank him warmly. I would also like to thank an anonymous referee who made constructive comments.

Compliance with Ethical Standards

Conflict of interest The author declares that he has no conflict of interest.

---

[4] As it is detailed in Appendix, Popper's interpretation is an orthodox interpretation and is clearly realist. On the contrary, the pragmatist interpretation is also an orthodox interpretation but it is instrumentalist.

Appendix: Examples of Interpretations

In order to illustrate the distinction between orthodox and heterodox interpretations, I will give examples of the two types of interpretations. Because one interpretation can have different variants, the following presentation will depend on the choosen variants. This is not a problem because my goal is only to illustrate the distinction between the two strategies, it is not to discuss any particular version and all its variants. Furthermore, I choose some versions because they are useful to illustrate the distinction. I don't want to deny that each of them may have its own difficulties and that its advocates have to solve some conceptual or physical problems. Once again, my goal is only to illustrate the distinction between orthodox and heterodox interpretations of Quantum Mechanics.

First I will give four examples of orthodox interpretations of Quantum Mechanics, that is to say four examples of quantum versions that keep the quantum principles but change the domain of validity of one (or more) of them.

The first example is Bohr's interpretation of Quantum Mechanics ([6]). He opposes microscopic and macroscopic levels and said that quantum mechanics concerns only the microscopic level, where the Planck constant cannot be neglicted. On the contrary, macroscopic phenomena should be described by classical physics, not by Quantum Mechanics, because the Planck constant can be neglected for macroscopic phenomena. In other words, Bohr limits the domain of validity of all the quantum principles to microscopic level. In this approach, the Measurement Problem has no reason to appear. Indeed the second description of a quantum measurement in the Measurement Problem supposes that a measurement apparatus can be treated as a quantum system. Yet a measurement apparatus is a macroscopic system. So, according to Bohr's interpretation, its behavior should not be described by the quantum laws and it should not be any Measurement Problem.

The propensionist interpretation developed by Karl Popper ([25]) is also an example of orthodox interpretation. This interpretation is a realist interpretation of the quantum principles. One of the key features of this interpretation is that the state function that is associated with a system doesn't represent the physical state of this system but only the propensions attached to the system (and to the whole physical situation). Thus the Scrödinger equation does represent the evolution of the state of the system, but only of the propensions. According to this interpretation, the contradiction between Principle III and Principle IV is supposed to disappear because these principles don't have the same meaning: one is about the state of the system, the other is about the propensions. Thus, during a measurement, the physical state of the system is described by Principle III, and only by it. The description of a quantum measurement by the Principle IV is meaningless in this interpretation.

A third example of an orthodox interpretation is given by Rovelli's interpretation [27]. According to this interpretation, the two descriptions involved in the Measurement Problem are not seen from the same point of view. Each of them is true relatively to its proper observer. The key of this approach is to consider that each description is dependent of a specific observer, that is to say: the descriptions are not "observer independent" and depend on two different observers. The use of Principle 3 (first description) or the use of Principle 4 (second description) are thus governed by the reference to an observer (or a point of view). This regulation tries to solve the problem: there are two different descriptions that are not true within the same conditions. We do not have to reject any of the quantum principles, we have to specify the conditions to which we can use it[5].

The pragmatist approach [4] is also an example of orthodox interpretation. This interpretation tries to make explicit the pragmatic meaning of the terms used by the researchers in microphysics and to give them a pragmatic definition, based on human action. Besides, this interpretation divide any experiment into four chronological phases: the preparation (wich is a set of sequences of precise and controlled experimental operations), the intermediate phase (during this phase, the prepared system is free to evolve without any experimental operation), the measurement (which is a set of experimental operations producing a macroscopic event), and the observation and the statement of the outcome. According to this interpretation, the pragmatist meanings of all the important terms of the theory are sufficiently determined to make the difference between all the phases and to know when the evolution is driven by Principle IV (as in the second phase) or by Principle III (as in the third phase). In terms of human actions, we know when we do a measurement and must use only Principle III. Thus, according to this interpretation, the contradiction of the Measurement Problem is supposed to disappear.

The previous examples illustrate the orthodox interpretations. Now I will give three examples of heterodox interpretations. A first example is given by Bohm's interpretation [5]. In this interpretation, the physical matter is supposed to be composed of particles that have determined position and velocity at any moment. A first modification to the mathematical formalism concerns Principle 1: a system S is not only associated to a state vector $|\Psi\rangle$ but also to a function $x(t)$ which represents the position of the system S. Futhermore, the position of a particle is supposed to be guided by a pilot wave (as in De Broglie's version). Thus a second modification of the mathematical formalism is made: a new equation, called "guiding equation", that described the evolution over time of the positions of every particles, is added to the standard formalism.

A second example is given by Everett's interpretation [9] and its variants. According to the Everett's interpretation, the Principle III is removed and the right description of a quantum measurement is the description given by Principle IV. We must not consider that only *one* outcome: *all* the possible outcomes are superposed. Because Principle III is removed, the contradiction of the Measurement Problem doesn't exist anymore. The variants of Everett's interpretation (like [7]) tries to explain why we observe only one result by saying that the possible outcomes don't occur in the same "world" (or "universe"). For example, if we measure the spin of an electron, in a branch we will find the result "+" and in another branch we will

---

[5] Rovelli goes a step further because he tries to derive the formalism from two principles centered on the notion of information but here we are not interested in developing this part of his work.

find the result "−". contrary to Principle 3, all the possibilities are realized but not in the same “world” (or “universe”).

We can also try to replace Principle 4 (the Schrödinger’s equation) by another equation. This way was proposed by Ghirardi et al. [13]. In this version, the fundamental idea consists in supposing that spontaneous collapses can occur randomly for any particle that compose a quantum system. “Spontaneous” means that it can occur without any interaction with another system. “Collapse” means that the concerned particle becomes localised in a small region of space. This hypothesis leads to modify the standard Schrödinger’s equation. Without entering too technical aspects, we can say that the standard Schrödinger’s equation can be written for the density operator ρ as follow: $\frac{d\rho(t)}{dt} = -\frac{i}{\hbar}[H, \rho]$ (this formula is equivalent to P_4). In the GRW version, for a system composed of several particles, it is replaced by: $\frac{d\rho(t)}{dt} = -\frac{i}{\hbar}[H, \rho] - \sum_{k=1}^{n} \lambda_k(\rho - T_k(\rho))$, where λ_k is a numerical parameter and $T_k(\rho)$ expresses mathematically the spontaneous localisation process of the k^{th} particle. $T_k(\rho)$ has the effect to change a pure state into a mixed state, that is to say: a state without quantum interferences. For a microscopic system, the probability of a spontaneous collapse is very low. But for a macroscopic system, because of the number of particles, the probability is very high. This is why, according to this interpretation, neither a macroscopic system nor a measured system (that is to say: a system in interaction with a measurement apparatus), are in entangled state: spontaneous collapses occur with a probability almost equal to one and the system is supposed to in a classical state.

References

1. Aspect, A., Grangier, P., Roger, G.: Experimental realization of Einstein–Podolsky–Rosen Gedankenexperiment: a new violation of Bell’s Inequalities. Phys. Rev. Lett. **49**, 91–94 (1982)
2. Aspect, A.: Bell’s inequality test: more ideal than ever. Nature **398**, 189–190 (1999)
3. Beveratos, A., Brouri, R., Gacoin, T., Villing, A., Poizat, J.-P., Grangier, P.: Single photon quantum cryptography. Phys. Rev. Lett. **89**, 18 (2002)
4. Bächtold, M.: Interpreting quantum mechanics according to a Pragmatist approach. Found. Phys. **38**(9), 843–868 (2008)
5. Bohm, D.: A suggested interpretation of the quantum theory in terms of ’hidden’ variables. Phys. Rev. **85**, 166–179 (1952)
6. Bohr, N.: Discussion with Einstein Albert Einstein: philosopher-scientist. In: Schilpp, P.A. (ed.) The Library of Living Philosophers, Open Court, pp. 199–241. Tudor Publishing Company, New York (1951)
7. DeWitt, B.S., Graham, N. (eds.): The Many-Worlds Interpretation of Quantum Mechanics. Princeton University Press, Princeton (1973)
8. Dirac, P.A.M.: The Principles of Quantum Mechanics. Oxford University Press, Oxford (1930)
9. Everett, H.: ’Relative State’ formulation of quantum mechanics. Rev. Mod. Phys. **29**, 454–462 (1957)
10. Georgescu, I.: Foundations of quantum mechanics. Nat. Phys. **10**, 253 (2014)
11. Friedman, J.R., Patel, V., Chen, W., Tolpygo, S.K., Lukens, J.E.: Quantum superposition of distinct macroscopic states. Nature **406**, 43–46 (2000)
12. Gerlich, S., Eibenberger, S., Tomandl, M., Nimmrichter, S., Hornberger, K., Fagan, P.J., Tüxen, J., Mayor, M., Arndt, M.: Quantum interference of large organic molecules. Nat. Commun. **2**, 263 (2011)

13. Ghirardi, G.C., Rimini, A., Weber, T.: Unified dynamics for microscopic and macroscopic systems. Phys. Rev. D **34**, 470–491 (1986)
14. Grangier, P., Roger, G., Aspect, A.: Experimental evidence for a photon anticorrelation effect on a beam-splitter: a new light on single-photon Interferences. Europhys. Lett. **1**(4), 173–179 (1986)
15. Guerlin, C., Bernu, J., Deléglise, S., Sayrin, C., Gleyzes, S., Kuhr, S., Brune, M., Raimond, J.-M., Haroche, S.: Progressive field-state collapse and quantum non-demolition photon counting. Nature **448**, 889–893 (2007)
16. Haroche, S., Raimond, J.-M.: Exploring the Quantum. Atoms, Cavities and Photons. Oxford University Press, Oxford (2006)
17. Jacques, V., Wu, E., Grosshans, F., Treussart, F., Grangier, P., Aspect, A., Roch, J.-F.: Experimental realization of Wheeler's delayed-choice Gedanken experiment. Science **315**, 966–968 (2007)
18. Kuhn, T.: The Essential Tension. Tradition and Innovation in Scientific Research (1959). In: Kuhn, T. (ed.) The Essential Tension. Selected Studies in Scientific Tradition and Change. The University of Chicago Press, Chicago (1972)
19. Leggett, A.: J. Phys. **14**, 415 (2002)
20. Leggett, A.: Nonlocal hidden-variable theories and quantum mechanics: an incompatibility theorem. Found. Phys. **33**(10), 1469–493 (2003)
21. Ourjoumtsev, A.: Generation of optical Schrödinger cats from photon number states. Nature **448**, 784–86 (2007)
22. Pan, J.-W., Bouwmeester, D., Daniell, M., Weinfurter, H., Zeilinger, A.: Experimental test of quantum nonlocality in three-photon Greenberger–Horne–Zeilinger entanglement. Nature **403**, 515–519 (2000)
23. Paul, T.: A propos du formalisme mathématique de la Mécanique Quantique. Géométrie de la cognition, Hermann, Paris, Logique et Interaction (2009)
24. Popper, K.: The Logic of the Scientific Discovery. Basic Book, New York (1959)
25. Popper, K.: The Postscript to The Logic of Scientific Discovery, III Quantum Theory and the Schism in Physics. Hutchinson and Company, London (1982)
26. Putnam, H.: A philosopher looks at quantum mechanics (again). Br. J. Philos. Sci. **56**, 615–634 (2005)
27. Rovelli, C.: Relational quantum mechanics. Int. J. Theoret. Phys. **35**, 1637–678 (1996)
28. Santori, C., Fattal, D., Vuokovic, J., Solomon, G.S., Yamamoto, Y.: Indistinguishable photons from a single-photon device. Nature **419**, 594–97 (2002)
29. Schrödinger, E.: Die gegenwärtige Situation in der Quantenmechanik. Naturwissenschaften **23**(48), 807–812 (1935)
30. Schrödinger, E.: Are they quantum jumps. Br. J. Philos. Sci. **3**, 109 (1952)
31. Shadbolt, P., Mathews, J.C.F., Laing, A., O'Brien, J.L.: Testing foundations of quantum mechanics with photons. Nat. Phys. **10**, 278–286 (2014)
32. Sinha, U., Couteau, C., Jennewein, T., Laflamme, R., Weihs, G.: Ruling out multi-order interference in quantum mechanics. Science **329**(5990), 418–421 (2010)
33. Sychev, D., Ulanov, A., Pushkina, A., et al.: Enlargement of optical Schrödinger's cat states. Nat. Photon. **11**, 379–382 (2017)
34. Tittel, W., Brendel, J., Zbinden, H., Gisin, N.: Violation of Bell inequalities by photons more than 10 km apart. Phys. Rev. Lett. **81**(17), 3563–566 (1998)
35. von Neumann, J.: Mathematische Grundlagen der Quantenmechanik. Springer, Berlin (1932)
36. Zeilinger, A.: Experiment and the foundations of quantum physics. Rev. Mod. Phys. **71**, 288–297 (1999)