A CHAPTER OF THE DEBATE BETWEEN REALISM AND ANTI-REALISM IN THE BEGINNINGS OF QUANTUM MECHANICS

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ABSTRACT: The purpose of this article is to present the debate established by realistic and anti-realist interpretations in the field of quantum mechanics. On the side of anti-realism, we chose Niels Bohr's interpretation of complementarity given its precursor character, as well as because of the great influence it had on other orthodox interpretations of quantum mechanics. Known as Copenhagen interpretation, its anti realism is characterized, among other things, by conceiving the impossibility of the existence of entities that are not captured by the subject through measuring instruments. On the other hand, realistic interpretations conceive that such entities are real objects, whose existence is independent of the mind. Such interpretations arose in response to the anti realism of entities and were established for representing a counterpoint, as well as a rupture with the Copenhagen monocracy. We will present here as examples of this counterpoint: the EPR paradox, D. Bohm's hidden variables, J. Bell's inequalities and H. Everett's relative states. In general terms, the purpose of this article is not to present the defense of a thesis, nor will we discuss in depth the arguments against the so-called Copenhagen interpretation. We will propose a presentation about the main interpretations that are contrary to the monocracy of the Copenhagen interpretation and we will deal with the developments that affected the fall of that same interpretation.

KEYWORDS: Anti-realism, Copenhagen Interpretation, Realism, EPR Paradox, hidden variables, inequalities, relative states.

1. Introduction

The Copenhagen interpretation or complementarity interpretation influenced and led orthodox interpretations of quantum mechanics in the 20th century[2]. Such interpretations advocate, among other things, a commitment to wave-particle dualism, as well as the anti-

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[2] Conscious of the positions that contradict our point of view, as is the case of Howard (2004), even so, we will maintain our position that is exactly opposite to the Howard's view that, what was called in his article (see references) of "Copenhagen spirit", despite the romanticism that underlies it, does not differ from what its critics call "Copenhagen interpretation", whose characteristics have been exhaustively described by the literature and are led by N. Bohr's complementary interpretation. In this way, we will maintain the agreement with authors who share the opposite view from Howard (2004), cited by him in his article, as is the case of Heisenberg (1955), Bohm (1957a), Hanson (1958, 1959), Feyerabend (1973) and Popper (1957, 1959, 1967, 1982), but which, due to the purposes of the article, will not be addressed here. Likewise, we do not agree with Bohr's interpreters that brings him closer to a Kantian or Neokantian position than to a positivist position such as the cases of Folse (1978), Honner (1982, 1987), Faye (1991), Chevalley (1994) and Bitbol (2000c, 2009).

realism of entities and substances. Under the list of orthodox interpretations, according to Pessoa Jr. (2006), there are some other interpretations, namely: the positivist wave interpretation, the subjectivist interpretation, the macrorealistic interpretation of complementarity, the eclectic interpretation, the realistic readings of complementarity, the radical instrumentalism, the stroboscopic interpretation, the interpretation of the S-matrix and the interpretation of the sum over stories. It is not our aim here to address each of these component interpretations of the orthodoxy of quantum mechanics. Our intention will be to approach the interpretation of complementarity, to present the anti-realist character that underlies it and that influenced a range of other interpretations and to demonstrate that such interpretation does not constitute the end of the interpretations of quantum mechanics, therefore, it does not constitute a truth of faith. To Bohr's anti-realism, alternative interpretations were presented, putting the monocracy of Copenhagen interpretation in check and enabling a realistic reading of quantum mechanics.

The anti-realism which we think Bohr's thinking is part is the anti-realism of entities or epistemological idealism, in the words of Mehlberg (1980). In this anti-realism we find the thesis that it is impossible to know entities that are independent of any knowing subject – they only exist because we know them. We will outline here our starting point, so that interpretive mistakes are resolved at the outset and that our position is previously fixed in relation to other researchers. We are aware of the various anti-realisms that present themselves in the field of the philosophy of physics – subjectivist, objectified, partial, transforming, creative, voluntarist anti-realism, etc. – however, as we said, our interest will be restricted to the anti-realism that concerns the entities and their dependence on the knowing subject. In this type of anti-realism, two positions stand out: a) that there is no reality that is independent of the mind; b) that the mind has an essential role in the constitution of the world[3]. Such interpretations, in addition to being common in physical theories involved with mysticism, such as those in which the mind plays an essential role in the unfolding of quantum phenomena, also include some orthodox theories that are based on the ideal that mathematical formalism should handle a supposed reality, but that do not ensure that such equations relate to reality itself, that is, they do not assume a realistic perspective regarding unobservable entities. This type of anti-realist theory ends up working much more as a fabrication of reality, since formalism provides intelligibility

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[3] We emphasize that the complexity of the Bohrian position cannot be synthesized only in these two characteristics of anti-realism, however, this will be our point of support, given our intention to deal here only with the anti-realism of entities and substances.

and universality to the theory, but, in an *ad hoc* way, introduces additions that are impossible to test, but that serve to solve what is problematic.

The anti-realism presented here is, therefore, in opposition to the realism of entities. This type of realism advocates that everything that exists can be reduced to physical realities, such as matter, energy, entropy, fields, etc. and that atomic entities are real objects that are independent of our mind. It is an epistemological conception that was conventionally called entity realism, this to differentiate from the dozens of realisms found in the literature relevant to the philosophy of physics (ontological, objectivist, potential, relational, metaphysical, harmonic, communicable, unsubstantiated, axiological, symbolic, etc.). Such realistic physicalist approach cannot be confused with positivism, which is a different conception. Positivism, in scientific thought, has as its fundamental task the positive description of natural phenomena from the data of experience. The positivist fixes himself on the observations, on the *positive data* obtained by the scientific instruments and declares as *metaphysical* any theory that recognizes the existence and the cognoscibility of objective reality based on unobservable premises. This is the perspective maintained by Pessoa Jr. (2001) in regard to the interpretation of complementarity or Copenhagen interpretation. According to him, the idealistic epistemological (or anti-realism) stance taken by Bohr in the interpretation of complementarity is a positivist stance, since his "theory describes only observations, and it makes no sense to ask how the unobserved reality is" (PESSOA JR., 2001, p. 164)[4]. Thus, any realism in Bohr's interpretation of quantum mechanics must be discarded since, unlike positivism, realism can maintain a realistic perspective of unobservable entities. This is not the case with Bohr's thinking.

2. The Interpretation of complementarity of Niels Bohr

It was in September of 1927, in Como, Italy, during the *International Physics Congress* held in commemoration of the centenary of Alessandro Volta's death (1745-1827), that Niels Bohr, for the first time, presented his formulation of the complementarity. Most of the founders of Quantum Theory were gathered, except Einstein and Ehrenfest, who would meet Bohr at the *5th Solvay Conference*, in Brussels, in the following month, where Bohr's lecture would be repeated. In a lecture entitled *The Quantum Postulate and the Recent Development of Atomic Theory*, Bohr gives a summary of the state of the art of Quantum Theory discussing about its contemporary problems: the uncertainty principle, the development of matrix mechanics, the

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[4] "However, after the measurement, Bohr accepted the use of retrodition" (PESSOA JR., 2006, p. 14).

wave mechanics, the problems of Schrödinger's interpretation, the stationary states of an atom and about the future perspectives of Quantum Theory.

Bohr deals with all themes, emphasizing the basic differences between the classical and quantum descriptions of physics: he discusses the discontinuity characteristic of quantum processes, which is unfamiliar to classical theories; he deals with the renunciation that the quantum postulate makes about the spatiotemporal coordination of atomic processes; he addresses the interaction between the observation agent and atomic phenomena; he expresses his anti-realism by stating that it makes no sense to attribute reality to the physical object independent of an observer: "(...) an independent reality in the ordinary physical sense can neither be ascribed to the phenomena nor to the agencies of observation" (BOHR, 1928, p. 580); he discusses the inherent irrationality in the quantum postulate concerning the possibility of cutting between the subject and the quantum object at any point in the chain that joins the two[5]; he discusses about a physical system that requires the elimination of all external disturbances, in this case, about the Schrödinger equation or other type of unitarity evolution that applies to closed systems; he also deals with the system in which there is an interaction with the measuring device, where a deterministic equation is not applied but a projection postulate: "(...) in order to make observation possible we permit certain interactions with suitable agencies of measurement, not belonging to the system, an unambiguous definition of the state of the system is naturally no longer possible, and there can be no question of causality in the ordinary sense of the word" (BOHR, 1928, p. 580). Here Bohr introduces his first statement of complementarity:

> The very nature of the quantum theory thus forces us to regard the space-time coordination and the claim of causality, the union of which characterizes the classical theories, as complementary but exclusive features of the description, symbolizing the idealization of observation and definition respectively. (BOHR, 1928, p. 580)

It is a statement that involves Bohr's first type of complementarity between a pair of characteristics that are consistent in classical physics, namely, space-time coordination and causality - which in this quote should be understood as "determinism" - or between *observation* and *definition*. "Indeed, in the description of atomic phenomena, the quantum postulate presents us with the task of developing a 'complementarity' theory the consistency of which can be judged only by weighing the possibilities of definition and observation" (BOHR, 1928, p. 580).

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[5] Thesis of psychophysical parallelism that was formally developed later by von Neumann – not by Bohr – and popularized by Fritz London and Edmond Bauer in 1939.

> An isolated system preserves energy and momentum, and therefore it is possible to say that it satisfies the causality. However, as it cannot be observed, it is not possible to associate a spatial position and temporal instant to it. On the other hand, when observed, a system starts to have a spatiotemporal coordination (given by the result of the measurement), but its state (after the reduction) did not evolve from the previous state according to the law of causality (that is, in a determinist way). (PESSOA JR., 2019, p. 94)

Bohr later abandoned the first formulation of complementarity, since, for an anti-realist position such as his, this notion made a distinction between an atom while existing and the same atom while known, which did not make sense. “Only from a realistic point of view is possible to give meaning to this 1st type of complementarity” (PESSOA JR., 2019, p. 94).

Bohr presents a second type of complementarity and this one involves the question of *complementarity between particle and wave*. This type of complementarity occurs against the grain of classical physics in which wave and particle are mutually exclusive elements. Bohr says:

> The problem of the nature of the constituents of matter presents us with an analogous situation. The individuality of the elementary electrical corpuscles is forced upon us by general evidence. Nevertheless, recent experience, above all the discovery of the selective reflection of electrons from metal crystals, requires the use of the wave theory superposition principle in accordance with the original ideas of L. de Broglie. Just as in the case of light, we have consequently in the question of the nature of matter, so far as we adhere to classical concepts, to face an inevitable dilemma, which has to be regarded as the very expression of experimental evidence. In fact, here again we are not dealing with contradictory but with complementary pictures of the phenomena, which only together offer a natural generalization of the classical mode of description. (BOHR, 1928, p. 581)

In Bohr’s opinion, the wave aspects (superposition principle in wave theory) and corpuscular aspects (energy conservation and momentum) of a quantum object that, although mutually exclusive, are complementary. The definition by the wave or particle aspect will depend on the type of experiment carried out by the observer: if he opts for the double-slit experiment, for example, it will show the wave nature; if it is the photoelectric effect experiment, on the other hand, nature will become corpuscular. This duality constitutes an “exhaustive” description of the quantum object, because they exhaust their possibilities of description, that is, there would not be any way more complete of representing a quantum entity. What Bohr does is to associate the *wave aspect with the definition* (the wave function with the unobserved). Later, he will define the *wave phenomenon* in the scope of observation (when interference occurs), as the *corpuscular phenomenon* (when it is possible to infer trajectories)

(PESSOA JR., 2000)[6]. What will be defined is that, for systems existing on the atomic scale, there is no predetermined value for physical quantities, it is the measurements that create reality.

The third type of *complementarity is the one among the incompatible observables*, as it is the case with position and movement. According to Bohr (1928, p. 581):

> The difficulties with which a causal space-time description is confronted in the quantum theory, and which have been the subject of repeated discussions, are now placed into the foreground by the recent development of the symbolic methods. An important contribution to the problem of a consistent application of these methods has been made lately by Heisenberg (Zeitschr. f. Phys., 43, 172; 1927). In particular, he has stressed the peculiar reciprocal uncertainty which affects all measurements of atomic quantities. Before we enter upon his results it will be advantageous to show how the complementary nature of the description appearing in this uncertainty is unavoidable already in an analysis of the most elementary concepts employed in interpreting experience.

We saw that Heisenberg's uncertainty principle advocated the impossibility of accurate and concurrent knowledge of the position and amount of movement of a particle. For Heisenberg, it is possible to use either the corpuscular or wave representation, since both provide the same experimental predictions. The third type of complementarity proposed by Bohr incorporated Heisenberg's physics into his own as a synonym for uncertainty. Here, complementarity occurs through the thesis that two conjugated quantities are complementary to each other in the sense that both are mutually exclusive, since the more precise determination of the value of one of them results in greater uncertainty with respect to the complementary quantity. Only according to the experiment, can we use either a corpuscular description, or a wave, but never both at the same time. According to Bohr, the use of a corpuscular or wave picture depends on the experiment in question and a "phenomenon" is the description of what must be observed based on the equipment used to obtain the observation, since they are complementary. The dismemberment of representations is merely a sign of the fact that, in the normal language available to us to communicate the results of our experiments, it is only possible to express the unity of nature through a complementary model of description.

> What Bohr was pointing to in 1927 was the curious realization that in the atomic domain, the only way the observer (including his equipment) can be uninvolved is if he observes nothing at all. As soon as he sets up the observation tools on his workbench, the system he has chosen to put under observation and his measuring instruments for doing the job form one inseparable whole. Therefore, the results depend heavily on the apparatus. (HOLTON, 1970, p. 155)

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[6] Note 10 of the translation into Portuguese of: BOHR, N. (1928), "The Quantum Postulate and the Recent Development of Atomic Theory". Trans. Osvaldo Pessoa Jr. *In*: *Fundamentals of Physics I - David Bohm Symposium*. Org. O. Pessoa Jr. São Paulo: Ed. Livraria da Física, 2000. p. 135-159.

In short, this notion of complementarity states that, in a sense, the unmeasured atom is not real: its attributes are created or defined in the act of measurement.

> When you ask, “What is light?” the answer is: the observer, his various pieces and types of equipment, his experiments, his theories and models of interpretation, and whatever it may be that fills an otherwise empty room when the lightbulb is allowed to keep on burning. All this, together, is light. (HOLTON, 1970, p. 156)

This type of interpretation is characteristic of a typical anti-realism professed by Bohr[7] and Heisenberg who maintains that the object has no existence that is independent of the subject who observes it. The case of light is a typical example of what is stated here: even if there are the room, the equipment - with its various parts and types -, theories, models and everything else that could fill the room, even so, without the existence of the subject who observes, which is complementary to everything else, the existence of the light object would definitely be compromised. Therefore, the philosophical developments of this notion of complementarity are directed in three ways: I) it professes a type of anti-realism where words like “particle” or “wave” do not designate anything about material objects or material properties of such objects, that is, they have no ontological *status*, they are only a description of certain experiments; II) it sacralizes the measuring instruments to the point that the act of observation and the figure of the observer become an integral part of the instrument itself, that is, it perverts the so-called scientific concept of dissociation between subject, object and scientific instruments, in addition to making measurement the alpha and the omega of knowledge, since there is nothing being observed besides observation itself; III) it compromises the notion of “scientific objectivity”, since the foundation of scientific knowledge shifts from the protagonism of the “object” to that of the “subject”. In fact, the obsolete distinction between subject and object is no longer valid in the view of the complementarists[8].

According to Schrödinger (1951, p. 154), what Bohr and Heisenberg “mean that recent discoveries in physics have pushed forward to the mysterious boundary between the subject

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[7] In the case of Bohr, anti-realism has been followed by a positivist background for placing in the measuring instrument full confidence in deciphering reality, that is, for sacralizing the measuring instruments.

[8] Later, already in 1955, when Bohr delivered a speech at a meeting of the Royal Danish Academy of Science in Copenhagen, he tried to defend himself against such accusation. According to him, “in view of the influence of the mechanical conception of nature on philosophical thinking, it is understandable that one has sometimes seen in the notion of complementarity a reference to the subjective observer, incompatible with the objectivity of scientific description (...). In quantum physics, as we have seen, an account of the functioning of the measuring instruments is indispensable to the definition of phenomena and we must, so-to-say, distinguish between subject and object in such a way that each single case secures the unambiguous application of the elementary physical concepts used in the description. Far from containing any mysticism foreign to the spirit of science, the notion of complementarity points to the logical conditions for description and comprehension of experience in atomic physics” (BOHR, 1995, p. 114-115).

and the object, which thereby has turned out not to be a sharp boundary at all". Bohr, on the other hand, reinforces his hope that "the idea of complementarity is suited to characterize the situation, which bears a deep-going analogy to the general difficulty in the formation of human ideas, inherent in the distinction between subject and object" (BOHR, 1928, p. 590). However, the idea of complementarity, despite being the foundation for the orthodox line of Quantum Theory, has nonetheless been an object of criticism by many of its contemporaries, as well as by recent scholars.

> [...] One may say that the concept of complementarity introduced by Bohr into the interpretation of quantum theory has encouraged the physicists to use an ambiguous rather than an unambiguous language, to use the classical concepts in a somewhat vague manner in conformity with the principle of uncertainty, to apply alternatively different classical concepts which would lead to contradictions if used simultaneously. (HEISENBERG, 1958, p. 179)

According to Bunge (2000, p. 237), when we look at the concept of complementarity, we see that it "is not a physical doctrine, but philosophical, because it does not refer to matter in motion, but to concepts and their verbalizations". It is precisely in positions like these that many physicists maintain their realism, not admitting the obscurantism underlying to some notions of Quantum Theory and opposing interpretations that demonstrate fragility in the use and application of terms.

3. The End of the Monocracy of the Copenhagen Interpretation

For many years, the Copenhagen interpretation orthodoxy has led debates in the sphere of quantum mechanics. This, however, did not guarantee its supporters the "tranquility" expected in times of normal science, in Kuhn's terms. Within orthodoxy itself, we have seen the unfolding of a series of interpretations that, if they do not contradict the interpretation of complementarity, diverge in substantial aspects related to it. But it was exactly from the outside that the orthodoxy led by Bohr suffered the greatest setbacks. Dissatisfaction with orthodox anti-realism caused physicist defenders of realist positions most of the time to raise their voices against Bohr's authority, which generated many unrest and more instability within orthodox interpretations of quantum mechanics. In this way, Einstein's local realism, the realism of Bohm's hidden variables, Bell's non-locality and Everett's deterministic realism gained voice, just to name a few examples. What is seen with these interpretations is that, many times, the anti-realism sustained by orthodox interpretations suffers from problems that sharpen the perception that there is something wrong with quantum mechanics.

What follows is intended to demonstrate that the orthodoxy led by Bohr is not a "truth of faith" and that other interpretations make good arguments to justify the need to break the monocracy of Copenhagen's interpretation. In general terms, what the arguments demonstrate is that, from the Copenhagen point of view, quantum mechanics must be incomplete, in Einstein's words.

3.1. The Einstein-Bohr debate on the fundamentals of Quantum Mechanics: the EPR paradox

To say that Einstein was an enemy of Quantum Mechanics is a huge mistake, because he was one of its founders. However, Einstein's realism did not agree with the uncertainties and anti-realism of Quantum Mechanics precisely because of his set of classical beliefs, Einstein sometimes fought in the arena of Quantum Physics and Bohr was one of his main intellectual opponents.

The interpretation of complementarity proposed by Bohr argues that the act of measurement influences a quantum system that makes it adopt characteristics that are observed *a posteriori*. For example, the manifestation of light, either as a wave or as a particle, depends on what the experimentalist makes it to be. While it does not manifest itself as one thing or the other, it is as if it were in a kind of limbo. Until they are observed, quantum systems remain as if in a state of superposition, that is, in a mixture of all possible states.

Three moments mark the history of the debates between Einstein and Bohr regarding the truths of Quantum Mechanics: *the 5th Solvay Conference on Physics* in 1927; *the 6th Solvay Conference on Physics* in 1930; and the study published in 1935 that became known as the Einstein-Podolsky-Rosen paradox (EPR paradox).

With the title *Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?* Einstein, Podolsky and Rosen's article (known as EPR), published on the *Physical Review* (1935), became bombastic by questioning the orthodox postulate according to which "*when the momentum of a particle is known, its coordinate has no physical reality*" (EINSTEIN; PODOLSKY; ROSEN, 1935, p. 778). According to Leon Rosenfeld, a friend of Bohr, "this onslaught came down upon us as a bolt from the blue" (ROSENFELD, 1967 *apud* WHEELER; ZUREK, 1983, p. 142).

As it is well known, the realistic attitude of Einstein, who believed in the objective physical reality of the "external world", and therefore in the objective reality of physical systems, independent of the events of observation, did not allow passive acceptance of the uncertainties of Quantum Mechanics that, in his conception, represented symptoms that something was wrong with the theory and with its interpretation. According to Herbert (1985, p. 201), Einstein argued that "the belief in an external world independent of the perceiving subject is the basis of all-natural science". On the other hand, Bohr "responded by comparing Einstein to the critics of his own relativity theory. He pointed out that thanks to Einstein's work, physicists have come to realize that space and time are not absolute but relative to an observer's state of motion" (HERBERT, 1989, p. 241). It should be noted, however, that, in Einstein's view, the problem was not with the correction of the theory[9], since it is resolved that the formalism of Quantum Mechanics is correct and that the statements underlying this formalism are consistent. What bothered Einstein - and this we have seen since the 1927 debate - was the question of the completeness of Quantum Theory, object of EPR questioning in the article in question.

> EPR do not contest quantum theory's competence to describe phenomena; Einstein, Podolsky, and Rosen claim, however, to have demonstrated the existence of certain "elements of reality" (in Einstein's words), parts of the world not directly observable which quantum theory simply leaves out. (HERBERT, 1985, p. 209-210)

For the authors, the *completeness condition* of a theory presupposes that "*every element of the physical reality must have a counterpart in the physical theory*" (EINSTEIN; PODOLSKY; ROSEN, 1935, p. 777). That is, there must be a correspondence between physical theory and objective reality in order to build a complete picture of the reality in question. In addition, the *criterion of reality* says that "*If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding lo this physical quantity*" (EINSTEIN; PODOLSKY; ROSEN, 1935, p. 777). The condition is necessary, but it is not enough to determine the completeness of a physical theory, since, by itself, it does not guarantee that the theory is complete in fact. For example, "two different elements of reality could have the same counterpart in a physical theory, so that the theory would not be complete, despite satisfying **C**[10]. The **C** condition also allows the theory to postulate non-existent entities" (PESSOA JR., 2019, p. 206). Copenhagen's interpretation of Quantum Mechanics, therefore, would be a correct interpretation in its formalism, but incomplete. This is what the EPR paradox tries to demonstrate.

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[9] "The correctness of a theory is judged by the degree of agreement between its conclusions and human experience" (EINSTEIN; PODOLSKY; ROSEN, 1935, p. 90).

[10] **C** = *completeness*, in the words of Pessoa Jr.

The EPR argument is based on the attempt to deny the completeness of Quantum Mechanics through the notion of correlated systems. We saw that in Quantum Theory the superposition of quantum states was seen as real: until a quantum system was measured, it remained in a state of superposition of all states. This points to the requirement of the correlation between the quantum system and the observer, since the existence of the quantum system (its exit from limbo) depends on the observer who proceeds to the measurement. As the observer measures a particle, the probabilities of the wave function of both particles collapse to consolidate the result. The wave function of the second particle collapses at exactly the same moment as the other, no matter how far apart the particles are. It was this type of conception that bothered Einstein's realism. "He could not imagine that a mouse could change the universe drastically simply by looking at it" (HERBERT, 1985, p. 174).

As it is conceived in Quantum Mechanics, this wave function collapse occurs instantly, at a distance and non-locally way. This suggests that the information of what was measured in *A* was transmitted instantly to *B*. Therefore, the question that remains is: would this type of action at a distance be possible, which causes two particles to interact instantly and non-locally, even though these particles are thousands of kilometers apart from each other? If such "entanglement", in Schrödinger's language, is possible, the notion that no signal carrying information can be sent faster than the speed of light (300 thousand km/s) falls apart.

EPR introduced a *locality* hypothesis in which it would be *impossible* for the measurement of a particle at one point *A* to have instantaneous reflections on another particle, at another point *B*, with a speed greater than the speed of light. "(...) Since at the time of measurement the two systems no longer interact, no real change can take place in the second system in consequence of anything that may be done to the first system" (EINSTEIN; PODOLSKY; ROSEN, 1935, p. 779). That is, if we decide to measure *A*'s position, we would find that *B* has a well-defined position, and if we measure *A*'s speed, we would find that *B* also has a well-defined speed. As the particles are separated by a great distance, the measurement in *A* cannot influence the position and speed values of particle *B*. In other words, *B* should initially have a well-defined position and speed at the same time. "The two particles in the imaginary experiment must already know what states they are in when they separate, he said. They carry this knowledge with them, instead of changing states simultaneously over remote distances" (BAKER, 2015, p. 78). Thus, EPR instituted a paradoxical situation of the existence of two contradictory notions: *locality* vs. *non-locality* - the first was admitted by most physicists of that time and the second was then embedded in the formalism of Quantum Mechanics. With the paradox in place, it was not difficult for EPR to present arguments that concluded that, by virtue of what has been demonstrated, Quantum Mechanics is incomplete.

> Let us go over the argument with a little more detail. On Earth, I can measure an observable A_1, and with that the state of particle nº 2 would reduce itself to a self-state of A_2. However, on Earth, I also could measure an observable B_1 that is incompatible with A_1 (in other words, whose associated operators do not commute), and so on the Moon the state of particle nº 2 would reduce to a self-state of B_2 (that is compatible with A_2). Now, check this: by the hypothesis of **locality**, nothing I do on Earth can instantly affect (or a speed bigger than the light) the **reality** on the Moon. But as I can measure both A_1 and B_1, on Earth, so both an A_2 self-state or a B_2 self-state have a simultaneous reality on the Moon, contrary to what Quantum Mechanics says (since A_2 and B_2 are incompatible). Thus, it would not be able to handle all the details of reality, it would be **incomplete**. (PESSOA JR., 2019, p. 205-206)

The EPR conclusion spells out an argument in a disjunctive form that is easy to analyze[11]. It is, in fact, an "exclusive disjunction", involved in the following premises of the authors: "Previously we proved that **either** (1) the quantum-mechanical description of reality given by the wave function is not complete **or** (2) when the operators corresponding to two physical quantities do not commute the two quantities cannot have simultaneous reality" (EINSTEIN; PODOLSKY; ROSEN, 1935, p. 780 – emphasis added). The truth table of an exclusive disjunction involving the premises (1) and (2) of the EPR conclusion, in propositional logic, is as follows:

1	**2**	**1 ⊻ 2**
T	T	F
F	T	T
T	F	T
F	F	F

This means that:

a) Because it is an exclusive disjunction, it is impossible for (1) and (2) to be true (T) at the same time, hence the result of the operation of disjunction will be false (check the first line of the table). This means that, if it is true (T) that "(1) the quantum-mechanical description of reality given by the wave function is not complete", then the proposition "(2) when the operators corresponding to two physical quantities do not commute the two quantities cannot have simultaneous reality" cannot be true;

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[11] Contrary to the amount of logical analysis, using classical (natural deduction proof) and non-classical (modal logic) analyzes, which have been presented as "deciphering" the EPR argument, which, many times, due to the degree of complexity in the understanding, it is preferable to read the original authors' own article (see, for example, McGRATH, 1978).

b) The propositions are mutually exclusive. This means that, because they are exclusive, affirming one of them presupposes denying the other. Thus, if it is true (T) that "(1) the quantum-mechanical description of reality given by the wave function is not complete", then, it is false (F) that "(2) when the operators corresponding to two physical quantities do not commute the two quantities cannot have simultaneous reality" or vice versa - or one thing, or the other, but not both - this is evidenced in the second and third lines of the table;

c) Finally, the negation of (1) implies the negation of (2), which forces EPR to state that (1) is true (T):

> Starting then with the assumption that the wave function does give a complete description of the physical reality, we arrived at the conclusion that two physical quantities, with noncommuting operators, can have simultaneous reality. Thus, the negation of (1) leads to the negation of the only other alternative (2). We are thus forced to conclude that the quantum-mechanical description of physical reality given by wave functions is not complete. (EINSTEIN; PODOLSKY; ROSEN, 1935, p. 780)

It is an interesting logical formulation, but it ends up revealing Einstein's discomfort with the intelligibility of this type of quantum entanglement. For him, as a convict realist, it was difficult to imagine the universe wrapped in a web of quantum connections, with an unknown number of particles communicating with its distant twins. Even so, for many, EPR would have been wrong: according to some, due to the defense of the principle of locality; according to others, due to their defense of the realistic position of the existence of reality independent of measurement.

> As soon as the paper was published, he [Einstein] received quite a number of letters from physicists 'eagerly pointing out to him just where the argument was wrong. What amused Einstein was that, while all the scientists were quite positive that the argument was wrong, they all gave different reasons for their belief!' (JAMMER, 1974, p. 187).

Despite the comments, criticisms and refutations to the EPR paradox, no answer was given shortly after the publication of the work. Everyone expected a manifestation from the father of the Copenhagen interpretation and that happened five months after the EPR article, when Niels Bohr published his response to the paradox, with the same title as the EPR article, and in the same journal where it was published. Much of Bohr's response is a reiteration of what he had already presented in response to Einstein's provocation in 1927, in the *5th Solvay Conference on Physics* – "the trend of the argumentation was in substance the same as that exposed in the foregoing pages (...)" (BOHR, 1949, p. 232). Thus, there were no surprises, since Bohr's strategy was to question the reality criterion of EPR. Bohr argues, therefore, that the EPR's reality criterion contains an ambiguity that makes it inapplicable in the considered case, since a physical influence *from the measurement* of one particle to the other particle *is excluded*. According to the Danish physicist, it is impossible for a quantum entity to have a property without being measured, that is, such property does not exist, it is not hidden waiting for a measuring device or any interference from the observer. Thus, “from our point of view we now see that the wording of the above-mentioned criterion of physical reality proposed by Einstein, Podolsky and Rosen contains an ambiguity as regards the meaning of the expression ‘without in any way disturbing a system’” (BOHR, 1935, p. 700).

We saw that the expression “without in any way disturbing a system” had been used by EPR [1935, p. 777]. Bohr considered, however, that the choice of measuring *A* or *B* constituted an influence on the very conditions that define the “phenomenon”, since different experimental arrangements would have to be used . Something that had already been anticipated by EPR when they claimed that “indeed, one would not arrive at our conclusion if one insisted that two or more physical quantities can be regarded as simultaneous elements of reality only *when they can be simultaneously measured or predicted*” (EINSTEIN; PODOLSKY; ROSEN, 1935, p. 780).

According to Pessoa Jr. (2019), Bohr would not, indeed, reject the “element of reality” of EPR, but the locality notion itself through a notion of totality of the phenomenon. However, “by ruling out a ‘mechanical disturbance’, Bohr seems to accept the principle of locality **LOC,** but soon after he states that the ‘definition’ itself of the system compound of two particles depends on the choice made by the experimentalist in relation to one of the particles, which is a way to reaffirm the *non-locality* character of Quantum Mechanics” (PESSOA JR., 2019, p. 212).

It is certain that, as Bohr himself said, “the discussions with Einstein which have formed the theme of this article have extended over many years which have witnessed great progress in the field of atomic physics. Whether our actual meetings have been of short or long duration, they have always left a deep and lasting impression on my mind (…)” (BOHR, 1949, p. 240). The impasse, however, was broken by the theoretical physical efforts of John Bell, in 1964, who created a test with which he *rejected* all models of reality with the property of locality. But this will be the subject of an upcoming article.

3.2. David Bohm: realism and non-locality in quantum mechanics

In 1951, David Bohm published the book *Quantum Theory*, the result of his courses in this discipline at Princeton University, where he presented an approach to the EPR paradox.

According to Bohm, EPR raised a serious criticism of the validity of the interpretation generally accepted in quantum theory, but that

> Their criticism has, in fact, been shown to be unjustified and based on assumptions concerning the nature of matter which implicitly contradict the quantum theory at the outset. Nevertheless, these implicit assumptions seem, at first sight, so natural and inevitable that a careful study of the points which the authors raised affords deep and penetrating insight into the difference between classical and quantum concepts of the nature of matter. (BOHM, 1951, p. 611)

Bohm seeks to present the reasons why such criticisms would be unjustified from an interesting point of view, given the different analysis he makes of the same problem in the articles published in 1952 on causal interpretation. In the 1951 analysis, Bohm identifies that EPR undertook to define the *criteria* for the evaluation of a physical theory using two explicit, but supported by two implicit, assumptions, which are an integral part of the treatment given by the authors, *but which were never explicitly stated*. Which ones would be?

As for the explicit criteria, here are those already stated by EPR: "(1) Every element of physical reality must have a counterpart in a complete physical theory" (BOHM, 1951, p. 612) and "(2) If, without in any way disturbing the system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of reality corresponding to this physical quantity" (BOHM, 1951, p. 612). As we have seen, the first of these criteria concerns the EPR *completeness* criterion and the second refers to the criterion used to recognize an *element of reality*. As for the two implicit assumptions, Bohm states them as follows:

> (3) The world can correctly be analyzed in terms of distinct and separately existing "elements of reality",
> (4) Every one of these elements must be a counterpart of a precisely defined mathematical quantity appearing in a complete theory. (BOHM, 1951, p. 612)

The assumption here (3) deals with the separability of the universe in terms of distinct and independent elements of reality. It is, therefore, a stronger realistic thesis of the criterion of the *element of reality*. The assumption (4) requires that the counterpart on the condition of completeness be precise. However, Bohm knew that these criteria should not be applied at a quantum level of *accuracy*.

Considering that the purpose of EPR was to show that the current interpretation of quantum theory was insufficient and that the wave function did not contain a complete description of physical reality, Bohm mentions that if his argument were correct, there would be a need to seek a more complete theory, through *hidden variables*. "If their contention could be proved, then one would be led to search for a more complete theory, perhaps containing something like hidden variables, in terms of which the present quantum theory would be a limiting case" (BOHM, 1951, p. 612-613).

To explore the theme, Bohm begins by considering an arbitrary observable *A* with a set of self-state, Ψ_a, which says that the system is in a quantum state in which observable *A* has the defined value *a*. In this situation, EPR would say that there is an element of reality in the system corresponding to observable *A*. However, Bohm also considers another observable *B*, which does not switch with *A*, so that there is no wave function for which *A* and *B* have values defined simultaneously. Adopting the implicit assumption (4), that every element of reality must be a counterpart to an *accurately* defined mathematical quantity that appears in a *complete* theory, then the usual assumption that the wave function provides a *complete* description of reality leads to the conclusion that *A* and *B cannot exist simultaneously*. This stems from the fact that the supposedly complete wave theory does not contain *accurately* defined mathematical elements, corresponding to the simultaneous existence of *A* and *B*. The consequence is that when *B* is measured and a defined value is obtained, the element corresponding to the observable *A* is destroyed (BOHM, 1951). To Bohm, it is natural to assume that this destruction is due to the *quanta* transferred from the measuring device to the system.

There are two themes involved, therefore, in Bohm's aforementioned considerations, namely, *hidden variables* and *non-locality*, which, consequently, end up being involved with the theme of *realism* – because in this theory of hidden variables the property to be measured is considered real and present in the object – and of *determinism* – since such a property can be determined with certainty, that is, all events are determined by causes.

We saw that, in 1923, de Broglie, in his doctoral thesis, had defended the idea that all matter consists of particles and waves, oscillating at a very determined frequency - an idea that would give him the Nobel Prize. In 1927, at the *Congress of Solvay*, Belgium, de Broglie presented a theory of hidden variables that maintained determinism and a realistic interpretation in which it would be possible to "view" atoms and electrons in the description of the reality behind the observations. Such reality would exist independently of the observer, at each instant and not only at the instant of observation. His conception, in addition to maintaining the notion of particle and wave, still conceived the continuous wave that guided the particle through space. It was the pilot wave. However, in this same Congress, Wolfgang Pauli (1900-1958) imposed a series of objections to de Broglie's realistic theory, which ended up causing him to give up his realistic dualist thesis. In this way, Bohr's complementarity interpretation came into effect and de Broglie's conception was shelved for about a quarter of a century.

In 1952, in an article entitled *A Suggested Interpretation of the Quantum Theory in Terms of "Hidden Variables"*, Bohm revive the theory of hidden variables and rediscovered, unintentionally – because he was not aware of these works –, the unpublished idea of de Broglie on the "pilot wave". The article was divided into two parts, the first of which corresponded practically to de Broglie's theory. Only when he sent the preliminary version to Pauli, Bohm knew about the criticisms that Pauli directed to de Broglie's work in 1927. The priority issue, however, was established, since de Broglie, in a statement to the Academy of Sciences, made them remember his old work. In a letter to Pauli, Bohm, according to Freire Jr. (1999), addresses the issue as follows:

> If a man finds a diamond and then abandons it, because he mistakenly concluded that it was a worthless stone, and if that same stone is found later by another man who recognizes its true value, wouldn't you say the stone belongs to the second man? I think the same reasoning applies to the interpretation of quantum physics. (FREIRE JR., 1999. p. 51)

However, the dispute was not present because, when the articles were published, Bohm recognized de Broglie's precedence. Both Pauli's objections to de Broglie's theory and von Neumann's objections to the existence of common objects and, therefore, to realism and determinism, were resolved by Bohm in his description of hidden variables of the quantum object (in this case, the position and velocity of the particles), as well as in the description of the hidden variables of the measuring device itself.

> Bohm's great advance over Broglie's was that he also took into account the hidden variables of the measuring device. This consideration of the hidden variables in the experimental context (that is, in the apparatus or in the environment), known as "contextualism", allowed Bohm to escape from von Neumann's proof of insolubility (...). Bohm also made clear the nonlocal character of his theory (...). (PESSOA JR., 2019, p. 236)

Bohm's theory, being deterministic, preserves the cause and the effect; in this theory the particle is traveling along a trajectory as in classical physics. Therefore, it eliminates the need for the collapse of the wave function. However, it does not prevent action at a distance, thus not circumventing the EPR paradox. If a detector is changed, the particle's wave field instantly changes as well. As a result, the theory is considered nonlocal.

Bohm's merit was to demonstrate that it was possible to think of a version of quantum mechanics involving hidden variables. The next step would be to test it. This task was left to John Bell.

3.3. Bell's Inequalities

John Stewart Bell worked at the *Conseil Européen pour la Recherche Nucléaire* (CERN)[12]. When on a sabbatical, in 1964, he decided to investigate the question of quantum reality, something he has been fond of since university, when he began his reflections on the foundations of quantum mechanics by studying the theories of von Neumann, de Broglie, EPR, etc. Beginning with von Neumann's proof that predicted that if quantum mechanics were correct, the existence of common objects could not be conceived to combine in a "reasonable way" – which denied realism and determinism –, Bell concluded that, even so, this test did not exclude objects that can change their attributes by reacting to the environment that surrounds them, as in the case of hidden variables that belong to the measuring device. It was precisely this loophole left by von Neumann that allowed the development of realistic models such as de Broglie's (which at that point had his deterministic conception trampled by Pauli's objections and von Neumann's own theorem, which made him give up this line of research) and David Bohm, which were built based on common objects.

During the preparation of the article on the von Neumann's proof, Bell began to think of a proof that could predict the *impossibility* of any reality that had certain physical characteristics. Therefore, he created a proof with which he *rejected* all models of reality with the property of locality (HERBERT, 1985). As we have seen, the locality is based on the notion that no information can be transmitted immediately and that the effects of nature propagate at the speed of light, therefore, at a finite speed. EPR had already dealt with the problem of locality and, due to the thought experiment, they came to the conclusion that the quantum theory would be incomplete, since it was shown to work in a "non-local" way, whose contradiction was demonstrated by the authors. On the other hand, in 1952 David Bohm had developed a version of quantum theory in which a reality could propagate instantly, that is, he developed a version in which reality is non-local. As Bohm had pointed out, his theory was contextual and also involved hidden variables that belonged to the measuring device. It was also realistic, as it dealt with a physical "reality", despite having hidden variables that could not be observed directly. Given this set of information that preceded him, Bell asked himself the following questions: would the non-locality of the theory of hidden variables be a characteristic of any quantum theory? If things exist without being observed, will they have to establish immediate action from a distance? Bell's idea was that any realistic physical theory, which wants to predict

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[12] Where is the Large Hadron Collider, the LHC, on the French-Swiss border, near Geneva, which has worldwide funding for research in high-energy physics.

everything that physics predicts, must be non-local, like Bohm's theory. This conception became known as *Bell's theorem*, which states that no local model can support quantum facts, so reality must be necessarily non-local. But, what is the real merit of Bell's theorem? What the theorem says is that if the hidden variables and the local realism were true, any decision made about measuring a nearby particle would not affect the property of a distant one, which Bell demonstrated that did not occur. Following that if a physical theory is realistic, then it is non-local. How is this demonstrated by the theorem? In summary, what the theorem says is that:

> There is a certain quantity whose value, for any local realistic quantum theory, is always less than or equal to the number 2 (it is, therefore, an inequality). As for the usual quantum theory, this value can be greater than 2. Bohm's theory is non-local realist, so the value can be greater than 2. Most physicists of the time interpreted Quantum Theory in a "non-realistic" way, so, for them, the value could also be greater than 2. (PESSOA JR., 2007-11, p. 37)

What does that mean? Bell's deduction involves the proportion with which correlated photons emitted by a single source, combine in polarization when reaching detectors far from the original source[13]. Its inequality describes the proportion expected in the photon correlation under well-defined conditions. The most interesting consequences of the theorem would happen if an experiment violated the inequality, that is, if it showed that x is greater than two ($x > 2$). In this case, we would have to give up one of two assumptions: a) of realism (things exist regardless of being observed); b) of the locality (the quantum world does not allow connections faster than light). As the polarization of photons derived from the EPR experience violates Bell's inequality, and as EPR insisted on the realistic posture, it is demonstrated that the notion of reality in its paradox is non-local. Since the phase is a quantum attribute that can be measured, and that is related to the polarity of the field associated with the photon, one can interpret the result of an experiment based on Bell's theorem as an indication that during the interaction between photons there is a phase entanglement. "What phase entanglement really is we may never know, but Bell's theorem tells us that it is no limp mathematical fiction but a reality to be reckoned with" (HERBERT, 1985, p. 223). If there is phase entanglement, there is action at a distance; if there is action at a distance, there is non-locality, that is, there are no hidden variables compatible with quantum theory – which goes against EPR.

According to Herbert (1989), Bell had confessed to him that:

> I had for long been fascinated by EPR. Was there a paradox or not? I was deeply impressed by Einstein's reservations about quantum mechanics and his views of it as an incomplete theory. For several reasons the time was ripe for me to tackle the problem head on. The result was the reverse of what I had hoped. But I was delighted

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[13] For details about the experiment see Herbert (1989, p. 253-270).

> in a region of wooliness and obscurity to have come upon something hard and clear. (HERBERT, 1985, p. 212)

Bell presented his theorem in 1964 in an article entitled *On the Einstein-Podolsky-Rosen paradox*. The theorem did not have much repercussion. He had written another one before that was essential to arrive at the result, but, due to the error of the journal editor, it ended up being published only in 1966. It was only in the 1970s that experiments confirmed that the value of the mentioned quantity could be greater than 2, contrary to what local realistic theories predicted. In 1972, John Clauser and Stuart Freedman, at the University of Berkeley, conducted an experiment to violate Bell's inequalities, which pointed to the non-locality of reality – ironically Clauser was a localist. However, the experiment remained misunderstood and disregarded by the physicists' community for about a decade. Only with the improvement of the optical equipment, among them, the *laser*, was it possible an experiment that became a classic of quantum mechanics. In 1982, Alain Aspect, in an experiment carried out with pairs of entangled photons, managed to violate Bell's inequalities, thereby demonstrating nature's non-local character: the data showed $x > 2$. This experiment was part of Aspect's doctoral thesis in which Bell participated. Finally, in 2007, the group of the Austrian physicist Anton Zeilinger verified the violation of inequalities using photons separated by 144 km. This type of experiment ends up inaugurating the area of quantum information – which involves quantum cryptography – and the search for ultra-fast quantum computers. The information may be sent and received by means of entangled photons that, subjected to Bell's inequalities, if violated, there will be no possibility of the message being unduly scrutinized.

The ontological question to be answered, however, is: why did nature choose a "ghostly action at a distance"?

3.4. Hugh Everett III and the interpretation of relative states

Hugh Everett III was the creator of the "interpretation of the relative states" of quantum mechanics. It is a view presented in a doctoral thesis at the end of 1955 and published in 1957, under the supervision of John Archibald Wheeler (1911-2008). Everett, Bohm and Bell are part of an important period of the rupture of the monocracy of Copenhagen's interpretation of quantum mechanics when they promoted the start of a critical environment about the fundamentals of orthodox interpretation of quantum theory, after the criticisms of EPR and Schrödinger in 1935. Due to the heterodox character of Everett's work, it was rejected by Bohr and his supporters. This work has interesting characteristics that conflict with the orthodox interpretation of quantum mechanics, but they open the door to a fertile field of research from then on. It is an interpretation that, among other things, discards the postulate of projection or the notion of collapse of the wave function, inserts the observer in a state of superposition, in addition to being deterministic and descriptive.

Everett's climb began in 1953 when he graduated, with *magna cum laude*, in chemical engineering from the Catholic University of America, Washington. From there, he had the recommendation to enter the doctorate at Princeton, which was accepted in the same year. In 1955, Everett already presented Wheeler with two manuscripts: the first of them about how to make a quantitative measure of the correlation between two systems and the second on probability in mechanical waves – which is a presentation of Everett's interpretation, without using mathematical formalism. Interestingly, Wheeler's answer is that, as for the first, he seemed practically ready to publish, but as for the second, he felt "frankly shy to show it to Bohr in his current form" and adds that his fear was justified "because of parts subject to mystical misinterpretations by many unqualified readers" (FREITAS, 2007, p. 53-54). But, why ask for Bohr's blessing? What is the justification for Wheeler's concern? What would be the mystical interpretations of said disqualified readers? According to Freitas (2007), Wheeler had devoted a great deal of appreciation and admiration to Bohr for a long time. He had spent a period of postdoctoral studies in Copenhagen examining the nuclear structure. With that, he ended up becoming the spokesperson for Bohr in the USA, nurturing a great feeling of friendship and admiration developed in the days of Copenhagen. "In this way it is possible to understand the need that Wheeler felt to see the interpretation of his pupil approved by Bohr" (FREITAS, 2007, p. 53).

Everett's thesis itself came out in late 1955 under the title *The theory of the universal wave function*. It is a text that presents its interpretation prepared, but which later suffered a reduction due to the non-acceptance of ideas by Bohr and his supporters. This "forced" Wheeler to take on the reformulation of the text and reduce it from 137 to only 36 pages, presenting it, in 1957, with a very neutral and generic title, *On the foundations of quantum mechanics*. The final version gained an explanation of Wheeler's interpretation of Everett, entitled *Assessment of Everett's "Relative State" Formulation of Quantum Theory*, which was sent to be published along with the thesis. Finally, the thesis was published, along with Wheeler's text, in *Reviews of Modern Physics*, a modest journal that would not allow the projection of Everett's ideas among physicists of his time. Instead, as the publication took place in the *Proceedings* of a conference on cosmology, it appeared that the article was restricted to that area, having little impact on the field of quantum physics, thus perverting the objective of the ambitious initial project.

But what was Everett's interpretation of relative states? Usually, this interpretation is known as the one that alludes to a set of ideas that deal with an infinity of coexisting "parallel universes". However, this is not Everett's original idea, and if it gained this connotation, it is due to the fact that Bryce DeWitt, together with his student Neill Graham, organized and edited, in 1973, a collection of the unpublished works of Everett and gave the title *The Many-Worlds Interpretation of Quantum Mechanics* (DEWITT; GRAHAM, 1973). However, it is important to note that there are fundamental differences between the interpretation of relative states and the interpretations of many-worlds (see BEN-DOV, 1990) and that Everett never used the term many-worlds. However, this distinction rarely occurs in the literature. The main difference between Everett's view and DeWitt's is that, according to Everett, there would be only one universe, with a behavior that is completely quantum, while DeWitt believed that each branch would be a different classic universe.

The starting point of Everett's work was the foundations of quantum mechanics, as conceived and formalized in von Neumann's work, which became objects of analysis and criticism regarding its flaws, especially regarding the postulate projection. It is known that one of the biggest problems of quantum mechanics is in the act of measurement, in what concerns the collapse of the wave. It is a problem that, due to the fact of not direct observation, arises a series of interpretations about what may have occurred that justifies such collapse. In general, the wave function expands linearly and deterministically, according to the Schrödinger equation, in a state of superposition of different states. However, the actual measurement act always finds a physical system in a defined state. Another possibility for the system to expand is to move instantly, during the measurement process, from a superposition of self-states to a specific self-state. If problems are not found in the first interpretation, since it is in accordance with Maxwell's electromagnetism, as well as with Newton's physics, for the second case, we have some problems to be solved by quantum mechanics, namely: how does the collapse of the wave function occur? What justifies a state of superposition if it collapses in a self-state? These problems were known as measurement problems and have occupied many physicists since the dawn of quantum physics.

In 1932, von Neumann introduced the postulate that he called "projection postulate", formerly known as "wave-packet reduction". According to this postulate, the Schrödinger equation would not be valid during the measurement processes. Thus, we would have two processes: the first in the absence of measurement, where the process would be governed by the Schrödinger equation, evolving in a linear, continuous and deterministic way; and the second occurring during the measurement, where the process would evolve governed by the projection postulate, being non-linear, discontinuous and probabilistic. “As the measurement interaction, governed by this postulate, is always made by an observer who is external to the quantum system and cannot be described by this formalism (at least not while in the role of an observer), this formulation can also be called formulation of external observation” (FREITAS, 2007, p. 16). The conventional formulation of quantum mechanics according to Everett, therefore, is this:

> We take the conventional or “external observation” formulation of quantum mechanics to be essentially the following: A physical system is completely described by a state function ψ, which is an element of a Hilbert space, and which furthermore gives information only to the extent of specifying the probabilities of the results of various observations which can be made on the system by external observers. (EVERETT, 2012, p. 175)

Even so, the projection postulate, which is responsible for making the connection between theory and experience, has its advantages, namely:

> To explain how the state evolves from a superposition to a specific value; in conjunction with Born’s rule, to bring out the probabilistic character of quantum theory, very well corroborated experimentally; and finally, it explains why we always get the same results when taking consecutive measurements. (FREITAS, 2007, p. 16)

However, if the projection postulate offers so many advantages to the measurement problem in quantum mechanics, what would have been the problem that Everett found in it? As for the first process, that is, *in the absence of measurement, the process would be governed by the Schrödinger equation, evolving in a linear, continuous and deterministic way*, for Everett, there is no problem – there is no experimental evidence to contradict this. However, in the second process that occurs *during the measurement, where the process would evolve governed by the projection postulate, being non-linear, discontinuous and probabilistic* the question that arises is: how to imagine a system that evolves from superposition to an autostate or reduced state? What causes this reduction? Is it the experimental apparatus? Is it the observer’s conscience as von Neumann suggested? It is questions like these that question the problem of measurement in quantum mechanics and was the object of reflection by Einstein, Schrödinger, Heisenberg and Bohr, for example. In the case of Borh, we already know in advance what his response was. According to him, this fact does not necessarily represent a problem, since it is an inherent characteristic of the system that, as a result, makes it special. However, for Everett, this poses deep problems that suggest revising the foundations of quantum mechanics. Another argument of the author is that the projection postulate is incompatible with the locality hypothesis, as it suggests an entanglement between particles that makes them communicate instantly, or in a "ghostly" way, as Einstein had suggested and criticized in EPR.

According to Freitas (2007), Everett points out that there are still three more problems for the quantum theory involving this type of evolution of the physical state of the system. They are:

a) What became known as the paradox of Wigner's friend, which is an unfolding of the paradox of Schrödinger's cat, which emerges when trying to deal with the evolution of the state using more than one observer.

> We can take any system S and put it to evolve in time until an observation made by A. However, we can take the system A + S as constituting another closed system, S', subject to observations of B. So we have the following question: does B have the system status function S' or not? If we deny that B can use quantum mechanics to describe the S' system, then the theory is incomplete because it does not allow observers like A, who are nothing but a (extremely complex) cluster of microscopic systems in the end, to be treated within the theory. In particular, there is the problem that the theory does not specify what can be dealt with quantum mechanics and what cannot, that is, what is an observer and what is a system. However, if we allow B to have access to the status function of S' AS+, then as long as B does not interact with this system, that is, does not make any observation about it, the system must evolve deterministically and no type of state reduction can occur, even though A is continuously making observations about the S system. In that case, we have two options. The first is that A is making an incorrect description of the S system, because as the evolution of both is deterministic, he could not have observed any kind of collapse. But if in fact A can observe collapses of the wave function of the S system and its description is correct, then we have the other option, that B cannot have access to the appropriate wave function to describe S', because according to his description no collapse may have happened and evolution has remained linear and deterministic. Thus, either A or B can have access to the objective quantum description of the system subject to observation, but never both simultaneously. (FREITAS, 2007, p. 18-19)

b) That of the impossibility of describing imperfect measurements using projection operators. In this case, the apparatus interacts with the physical system, which makes it impossible to know what "precisely the result marked on the apparatus is and what is the remaining state of the system". To be adequate, the theory should specify both, as well as "the probability of each particular reading happening, which it does not do" (FREITAS, 2007, p. 19).

c) The one against the formulation of external observation of quantum theory, with regard to the description of the closed universe using the presence of external observers.

> If the universe is a completely closed system, then there are no external observers to make the transition from one state to another, that is, to induce the collapse of the wave function and to obtain specific states, and the question remains why the universe does not seem to be in a superposition. (FREITAS, 2007, p. 19)

In short, the central thesis of the problems exposed here is involved in the question of how to apply quantum theory to isolated systems without the need for an external observer. It is because of these, and other issues, that Everett states that:

> (...) the Copenhagen interpretation is hopelessly incomplete because of its a priori reliance on classical physics (excluding in principle any deduction of classical physics from quantum theory, or any adequate investigation of the measuring process), as well as a philosophic monstrosity with a “reality” concept for the macroscopic world and denial of the same for the microcosm. (EVERETT, 2012, p. 255)

If so, what will be the proposed exit for Everett? According to him, there are two fundamentally different ways in which the state function can change:

> **Process 1:** The discontinuous change brought about by the observation of a quantity with eigenstates, ϕ_1, ϕ_2, ..., in wich state ψ will be changed to the state ϕ_j with probability $|(\psi,\phi_j)|^2$.
> **Process 2:** The continuous, deterministic change of state of an isolated system with time according to a wave equation $\partial\psi/\partial t = A\psi$, where A is a linear operator. (EVERETT, 2012, p. 175-176)

What Everett proposes, therefore, is to eliminate the postulation of process 1 and consider pure wave mechanics only the one of process 2, coinciding with the missing measurement process, according to von Neumann, which evolves in a linear, continuous and deterministic way. Thus, it is possible to anticipate that Everett will eventually circumvent the measurement problem, discarding the collapse process by reformulating the relationship between the measurement apparatus and the system, in such a way that a line of the laws of quantum mechanics is universal, that is, quantum systems would evolve linearly and deterministically, according to the Schrödinger equation. The universe as a whole must be described by a single wave function. And it is precisely the notion of “relative states” related to composed systems that gives us the justification for eliminating the process 1. According to Everett (2012, p. 180),

> (...) There does not, in general, exist anything like a single state for one subsystem of a composite system. Subsystems do not possess states that are independent of the states of the remainder of the system, so that the subsystem states are generally correlated with one another. One can arbitrarily choose a state for one subsystem, and be led to the relative state for the remainder. Thus we are faced with a fundamental relativity of states, which is implied by the formalism of composite systems. It is meaningless to ask the absolute state of a subsystem – one can only ask the state relative to a given state of the remainder of the subsystem

Relative states would be, therefore, a state where the state of the observer is defined in relation to the state of the system he observes. This notion of relative states becomes belligerent with orthodox interpretation when applied to macroscopic systems - something like Schrödinger’s cat - involving observers and measuring devices.

> It will suffice for our purposes to consider the observers to possess memories (i.e., parts of a relatively permanent nature whose states are in correspondence with past experience of the observers). In order to make deductions about the past experience of an observer it is sufficient to deduce the present contents of the memory as it appears within the mathematical model.
> As models for observers we can, if we wish, consider automatically functioning machines, possessing sensory apparatus and coupled to recording devices capable of registering past sensory data and machine configurations. We can further suppose that the machine is so constructed that its present actions shall be determined not only by its present sensory data, but by the contents of its memory as well. Such a machine will then be capable of performing a sequence of observations (measurements), and furthermore of deciding upon its future experiments on the basis of past results. If we consider that current sensory data, as well as machine configuration, is immediately recorded in the memory, then the actions of the machine at a given instant can be regarded as a function of the memory contents only, and all relevant experience of the machine is contained in the memory. (EVERETT, 2012, p. 183)

If so, in the interpretation of the relative states, the notion that the "collapse" occurs during measurements is just an illusion that is linked to our *trajectory of memory configurations*, that is, *all relevant experiences of the machine will be contained in the memory*. In this way, Everett affirms deterministic realism and avoids any anti-realist turn of events in the orthodox program of interpreting quantum mechanics.

In the case of the observer's relative state, the observer, when looking at the result of his experiment, would also enter a state of quantum superposition, and there would no longer be only one version, but two, of the same, that is, two branches, each one noticing a different result for the experiment. If there is no collapse – in experiments involving the properties of light, for example – there is no reason to talk about it, and much less about uncertainty. What happens is that on one branch an observer in a quantum superposition will observe it as a wave and, on the other branch, as a particle.

> We thus arrive at the following picture: Throughout all of a sequence of observation processes there is only one physical system representing the observer, yet there is no single unique state of the observer (which follows from the representations of interacting systems). Nevertheless, there is a representation in terms of a superposition, each element of which contains a definite observer state and a corresponding system state. Thus with each succeeding observation (or interaction), the observer state "branches" into a number of different states. Each branch represents a different outcome of the measurement and the corresponding eigenstate for the object-system state. All branches exist simultaneously in the superposition after any given sequence of observations. (EVERETT, 2012, p. 188-189)

Each branch must correspond to a result of quantum measurement and the observer's memory, in one of the branches, would not have access to the memory of the other, in another branch. In this way, the observer would have access to only one of the measurement results that was produced and, with that, to the consequent sensation of the occurrence of a collapse of the quantum state. In fact, it would have entered a macroscopic superposition and no collapse had actually occurred, only the appearance of that collapse.

As we have seen, the consequences of interpreting Everett's relative states were profound: he discarded the postulate of the projection and the consequent collapse of the wave function, placed the observer in a state of superposition, overthrew the notion of external observer to the system, presented a realistic, deterministic, linear and descriptive interpretation of quantum mechanics.

If Jammer believes that Everett's interpretation is not satisfactory even in relation to the "logical consistency and agreement with experience" (JAMMER, 1974, p. 513), even so, such an interpretation represented a major discomfort to Bohr's complementarity theory. As a result, the reaction that the Danish physicist and his supporters had to face the interpretation of relative states was expected, summarily rejecting it and making Everett's visit to Bohr in Copenhagen a real "hell". The consequence of such disappointment was that Everett left the field of physics and started his own company, Lambda Corp.114. After Bohr's visit, Everett never again worked on quantum theory issues. His disappointment with the whole process and the lack of repercussions for his innovative theory discouraged him from researching physics. He first went to work for the Pentagon in national defense and later continued to provide services to the American government through his companies.

4. Final Considerations

The birth of quantum mechanics brought with it a rich philosophical material with regard to the metaphysics of the nature of reality. It is precisely from the experimental confirmation of the reality of the behavior of the atom, sometimes as a wave, sometimes as a particle, that we saw problems appear that fed the physicists imagination and that filled the philosophers' eyes. Questions regarding the dual nature of the behavior of matter, uncertainty, complementarity and the place where the collapse of the wave function occurred broke the classic paradigm that made the world seem determined, continuous and local, for whose explanation it would be necessary to use causality and contact action. These problems raised by the new born quantum mechanics created a series of interpretations about the ultimate nature of reality to the point of being lost in the contingent of interpretive proposals. In this article, in brief terms, we wanted to emphasize the anti-realistic character of interpretations that compose the so-called quantum mechanics orthodoxy. Thus, dealing with Bohr's interpretation of complementarity is to advance the commitment that orthodox interpretations close to it have with the dualism and anti-realism of such interpretations. However, the realism advocated by classical physics had not been revoked and there were several attempts to demonstrate that the uncritical conversion to the Copenhagen school was meaningless, since, apparently, the propositions that underlie the arguments underlying the orthodox interpretations needed to be better qualified. Einstein will be the leader of the crusade that will try to demonstrate that quantum mechanics, as understood by orthodoxy, was incomplete. On the other side, Bohm, Bell and Everett presented themselves with proposals that maintain realism and “move away” the quantum mechanics from the ghost of idealism. However, as it can be seen, such interpretations, that were proposed to be realistic, ended up involving themselves with strange and confused terms that, it seems to us, do not constitute a reality beyond new formalisms. Thus, notions such as those of hidden variables, quantum entanglement and relative states do not seem to help us when we need a safe haven about the intimate reality of nature. It remains for us, therefore, to grasp the genius of an Einstein and a Schrödinger (who was not discussed in this article) who, while maintaining a philosophical view about their assessment of the successes of quantum mechanics, did not embark on the enthusiasm of most of their colleagues, who had the Copenhagen interpretation like a kind of mantra. The Copenhagen interpretation, as we have seen, had the merit of providing a fervent debate between realists and anti-realists, but, on the other hand, it also constituted a fertile ground for the emergence of the strangest and most esoteric interpretations of the quantum phenomena that, later, presented under the banner of quantum mysticism – with which the interpretation of complementarity is not involved, but whose influences can be perceived. However, this is a topic for another opportunity.

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