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INDETERMINATION AND POTENTIALITY IN QUANTUM PHYSICS
INDETERMINACIÓN Y POTENCIALIDAD EN LA FÍSICA CUÁNTICA

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Abstract: One of the main philosophical problems of quantum mechanics is understanding in what manner Schödinger's wave function can said to be real. In this paper I explore the ways in which the Aristotelian notion of potentiality could be used to understand the reality of the wave function, as suggested by Heisenberg in some of his writings. For this reason I sketch some of the potential complications in the interpretation of wave function while trying to develop Aristotle's philosophy of potentiality in relation to quantum mechanics. I will also attempt to demonstrate the connections of Popper's account of propensities with the notion of potentiality.

Key words: Aristotle, electron, Heisenberg, Popper, wave function.

Resumen: Uno de los principales problemas filosóficos de la mecánica cuántica es comprender de qué manera la función de onda de Schrödinger puede decirse que es real. En este artículo exploro el sentido en que la noción aristotélica de potencialidad podría utilizarse para entender la realidad de la función de onda, tal y como sugirió Heisenberg en algunos de sus escritos. Por esta razón trato algunas de los posibles problemas en la interpretación de la función de onda a la vez que intento desarrollar la filosofía de la potencialidad aristotélica en relación con la mecánica cuántica. También intentaré demostrar las conexiones entre las propensidades tal como las propone Popper y la noción de potencialidad.

Palabras clave: Aristóteles, electrón, Heisenberg, Popper, función de onda.

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1. Introduction

The birth and development of quantum mechanics in the 1920's and 1930's brought about various problems that questioned our comprehension of nature, and specifically the interpretation of high mathematical formalism that seemingly leads to a probabilistic theory. One of the main problems concerning quantum physics is how to interpret Schrödinger's wave function and the way it describes the physical world. In the foundational period of quantum mechanics there was a wide debate concerning which kind of reality we should attribute to the physical notions of "particle" and "wave" and how we should understand them in order to do physics. It seems that wave function describes the evolution of the quantic system, but it implies, among other problems, that there is a superposition of electron states before the observer measures a property of the system with some experiment[2]. Hence it is difficult to know for certain if the electron can be understood as a particle or as a wave, and which kind of reality corresponds to the wave function. On the other hand, it does not seem possible to say that quantum mechanics is just a mathematical formalism that must be interpreted as a probabilistic theory without reference to reality. In that case we would have to say that quantum mechanics tells us nothing about the world, but can only be used as a tool to make predictions. However, it seems strange that such a precise mathematical formalism is not describing something real[3].

In the following pages I will atempt to approach these problems in a realistic way. Assuming that the wave function describes something real, the question is therefore to know what kind of reality we are talking about when we apply the term real to the wave function. As I will try to show, this problem is connected with the question of the determinacy or indeterminacy in quantum physics.

In order to resolve these problems I will explore the Aristotelian notion of potentiality which, as a comprehensive tool, can help us to find an intermediate level of reality between being and not-being. Although this use of the term potentiality was suggested by Werner Heisenberg in

2. See Dirac, P.A.M.: The Principles of Quantum Mechanics. Oxford: Clarendon Press, 1978, pp. 34-36.

3. "I personally like to regard a probability wave, even in 3N-dimensional space, as a real thing, certainly as more than a tool for mathematical calculations. For it has the character of an invariant of observation; that means it predicts the results of counting experiments, and we expect to find the same average numbers, the same mean diviations, etc., if we actually perform the experiment many times under the same experimental condition. Quite generally, how could we rely on probabilty predictions if by this notion we do not refer to something real and objective?. Born, M.: Natural Philosophy of Cause and Chance. Oxford: Clarendon Press, 1949, pp. 105-106.

order to explain the collapse of the wave function, I think that a deeper reflection could also help to understand in which way we can say that the wave function is something "real". In this sense Popper's "propensity interpretation" of quantum mechanics is close to a potentiality/act interpretation of the physical world. As D'Espagnat pointed out, the Aristotelian notions of "potentiality" and "materia prima" could have an interpretative role to play in quantum mechanics, but it is necessary to reformulate them in a more precise way[4].

2. Historical approach to the problem of the wave function

As Jammer pointed out, the main problems to accept a totally realistic interpretation of the wave function (ψ) are that:

ψ is a complex function

ψ undergoes a discontinuous change during a process of measurement.

ψ depends on on the set of observables chosen for its representation, for example, its representation in momentum space differs radically from its representation in position space[5].

The wave function does not describe a particular event, but rather a range of possible events, and in its equation we find complex numbers that cannot describe something real at all ($\sqrt{-1}$). If the wave function is just a probability of knowledge, it could be said that it is just a theoretical (mathematical) model that helps to make predictions. However, it seems that the wave function, although describing a probability, it is also something real, or rather is describing some real properties of the physical world: otherwise it would make no sense its high predictive capacity.

Since Max Born interpreted the wave function in terms of probability, the question about realism/idealism and determinism/indeterminism has led to the emergence of different interpretations. The Copenhagen interpretation, which has been the most accepted among scientists, understands that there is a limit in our knowledge of reality, and it is not possible to define all the properties of the system, because when the observer makes an experiment there is a collapse in the wave function that alters it and "forces" the electron to manifest at one located point. Why does the electron appear at one or another particular point? According to the Copenhagen interpretation the reason would be the

4. See D'Espagnat, B.: On Physics and Philosophy. Princeton and Oxford: Princeton University Press, 2006, p. 459.

5. Jammer, M.: The Philosophy of Quantum Mechanics. New-York: Wiley-Interscience, 1974, p. 33.

indeterministic character of the quantum world. As a result the wave function helps to make predictions, but it is not possible to predict the result of the experiment in a totally precise way, because there is some kind of indetermination in the behaviour of the electron. The fact of subjecting the photon or the electron to an observation forces it entirely into one of its possible states, but the result of the observation cannot be predicted at all, since we can only know the possible states through a probability law[5]. Moreover, there seems to be a superposition of states previous to the observation by which any particle can be made to exhibit interference effects with itself.

One of the main interpretations of the Copenhagen school is Bohr's principle of complementarity. As he stated repeteadly[6], the notions of "wave" and "particle" shouldn't be seen as contradictory. Moreover, we need to use them as complementary notions in order to make science. It seems that in Bohr's view there is no possibility of finding a reasonable solution to the wave-particle duality and, as a result, we should put aside the question of whether the waves or particles are real. In this case, the words "particle" and "wave" wouldn't have an ontological status, but only an empirical one: since they are only entities entering the description of certain experiments. Although some kind of independent physical reality underlies Bohr's interpretation[7], it would be only in the sense that the particle/wave duality is related to the phenomena. It is not possible to give them some ontological status[8]. It is necessary, according to his view, to give up the causal description of the phenomena in terms of space and time. Although Bohr repeteadly explains that they are not contradictory visions, but complementary, he does not make clear in what sense they are possibly complementary. He just states that in their field of application both elementary particles and waves are in some sense real[9]. The principle of complementarity therefore could lead to an empiricist view of nature and science, as M. Bunge pointed out[10].

Whereas Bohr's principle of complementarity states that the wave and particle modes of description are complementary models, Heisenberg and Pauli thought that the wave nature of matter meant nothing more

6. See Dirac, P.A.M.: The Principles of Quantum Mechanics. Oxford: Clarendon Press, 1978, p. 7.

7. See Bohr, N.: La théorie atomique et la description des phénomènes. Paris: Gauthier-Villars, 1932, pp. 49-85.

8. See Folse, H. J.: The Philosophy of Niels Bohr, the Framework of Complementarity. Amsterdam: North-Holland, 1985, pp. 222-223.

9. See Bohm, D.-Hiley, B. J.: The Undivided Universe. An Ontological Interpretation of Quantum Theory. London and New York: Routledge, 1993, pp. 16-17.

10. See Bohr, N.: "Le postulat des quanta et le nouveau dévelppement de l'atomistique", in: Électrons et photons. Rapports et discussions (Solvay 1927), Gauthier-Villars, Paris, 1928, p. 244.

than the inherently random behaviour of entities that are particles[11]. As we will see, Heisenberg introduces the concept of potentiality as a possible way to understand the wave function. Although it is not clear in which way he thinks the potentiality to be real, I want to show that a deeper understanding of the notion of potentiality can bring light to understand the quantum world[12]. Close to Heisenberg's and Pauli's view we find Born's position, even though he is in favour of understanding that both the particle and the wave are in some sense real[13]. However, although there are still significant differencies of emphasis between these physicists it was clear that all of them shared a common interpretation[14].

As I have previously explained, one of the main problems of the Copenhagen interpretation is that it can lead to an instrumental view of science in which quantum mechanics could be interpreted as a mathematical formalism that helps to make predictions, but is incapable of describing the physical world as it is. However, if we want to admit that this mathematical formalism helps to describe and understand the physical world, it is then necessary to provide an interpretation that incorporates the wave-particle duality in a realistic manner. The wave function must have some kind of reality if it is to truely help to make predictions, and in the same way the particle must be also real.

An interesting interpretation can be found in De Broglie's pilot-wave theory. Although for a long time he admitted the Copenhagen interpretation (rejecting his previous ideas), he turned back later to a realistic way of understanding the waves and particles. Thus, he differentiated the ψ (epistemological) wave function from what he called the *u*-wave, which would be the real wave: "whilst the *u*-wave would be the true description of microparticles, the ψ-wave would be a ficticious wave with a subjective character but capable of supplying precise statistical information and still linked in some way with the *u*-wave"[15]. This ontological interpretation of

11. "It is not merely that the doctrine of complementarity stresses the doubtless active rôle of the experimenter, the active side of knowledge; it goes beyond this, asserting that obervations are the alpha and the omega of the knowledge, that there is nothing which is being observed, nothing beyond observation itself". Bunge, M.: "Strife about Complementarity" in British Journal for the Philosophy of Science 6, 1955-1956, p. 3.

12. See Holton, G.: Concepts and Theories in Physical Science. Reading: Addison-Wesley, 1973, p. 499.

13. See Bohm, D.-Hiley, B. J.: The Undivided Universe. An Ontological Interpretation of Quantum Theory. London and New York: Routledge, 1993, pp. 18-19.

14. See Born, M.: Natural Philosophy of Cause and Chance. Oxford: Clarendon Press, 1949, pp. 104-106.

15. See Hendry, J.: The Creation of Quantum Mechanics and the Bohr-Pauli Dialogue. Dordrecht: D. Reidel, 1984, p. 127.

both waves and particles has been further developed by Bohm[16]. However, once admitted that waves and particles are real, the problem would be to know how both of each relate to each other and, in the case of De Broglie's *u*-wave, how it is related with the ψ function[17]. In any case, it seems necessary to establish some metaphysical comprehension of the reality of waves and particles.

Schrödinger took another way of interpretating quantum mechanics based on the priority of the wave model. He viewed his ψ wave as a physical wave (a real wave[18]), abandoning completely any idea of localizing the particle in this wave, and forming a picture of the atom which made no place for localized particles[19]. Thus, his conclusion is that we shouldn't think that there is a "substratum" (a "material particle") behind the atomic level: "It is better to regard a particle not as a permanent entity but as an instantaneuous event"[20]. In this sense, the electrons are not particles, but forms (waves) without materiality in the sense that they don't have a specific location:

> It seems almost ludicrous that precisely in the same years or decades which let us succeed in tracing single, individual atoms and particles, and that in various ways, we have yet been compelled to dismiss the idea that such a particle is an individual entity which in principle retains its 'sameness' for ever. Quite the contrary, we are now obliged to assert that the ultimate constituents of matter have no 'sameness' at all[21].

However, Schrödinger's interpretation seems to be a strong phenomenalistic position according to which what we call reality are just our perceptions: "That is the reality that surrounds us: some actual perceptions and sensations become automatically supplemented by a number of virtual perceptions and appear connected in independent complexes, which we

16. De Broglie, L.: The Current Interpretation of Wave Mechanics. Amsterdam: Elsevier, 1964, pp. 38-39.

17. See Bohm, D.-Hiley, B. J.: The Undivided Universe. An Ontological Interpretation of Quantum Theory. London and New York: Routledge, 1993.

18. For some of the problems that arise from Bohm's interpretation see D'Espagnat, B.: On Physics and Philosophy. Princeton and Oxford: Princeton University Press, 2006, pp. 201-206.

19. "Something that influences the physical behaviour of something else must not in any respect be called less real than the something it influences –whatever meaning we may give to the dangerous epithet 'real'". Schrödinger, E.: "What is an Elementary Particle?" in Schrödinger, E.: Science, Theory and Man. London: George Allen and Unwin, 1957, p. 198.

20. See De Broglie, L.: "On the True Ideas Underlying Wave Mechanics" in De Broglie, L.: Heisenberg's Uncertainties and the Probabilistic Interpretation of Wave Mechanics. Dordrecht: Kluwer, 1990, p. xlii.

21. Schrödinger, E.: Science and Humanism, Cambridge: Cambridge University Press, 1951, p. 131.

call existing objects”[22]. In this way, his preference for the reality of the waves should be understood as some version of phenomenalism[23] in which reality (the waves) is something we cannot perceive directly, but through a process of “private sense-data”. Assuming that only the waves are real (in a very strange sense of being real), the particles would be just our way of perceiving the world, but not actually real. Nevertheless, Schrödinger philosophical statements are not clear at all, and I guess it would require a further development to understand them.

All these interpretations show that the questions that arise from quantum mechanics are not only physical problems, but also a metaphysical challenge[24]. The mathematical formalism of the wave function and several experiments show a counterintuitive behaviour of the elementary particles that seem to contradict the most basic principles of our knowledge of reality: that it should be determined and located in space and time.

The principle of no-contradiction, which is the basic premise of all science, points out that real beings are in a determined way, and not in two determined states at the same time. Nevertheless, what we can draw from Schrödinger’s equations is that the electron has not a determined state before we interact with it, and that the electron is in all its possible states (probability-wave) at the same time. Therefore, the electron is in all the possible states, and at the same time is not at all in any of them. The question that then arises is in which way we should think that this wave aspect is real. Here is where the Aristotelian notion of potentiality can be an interesting tool to understand it. Now I would like to analyze this notion ir order to find a metaphysical answer to the problem of indetermination and the possible states in the wave function.

3. Potentiality from a philosophical perspective

Heisenberg suggested in several passages of his philosophical writings that the Aristotelian notion of potentiality (*potentia*) could be useful to understand the problem of measurement and the wave/particle duality in quantum mechanics. Even though he didn’t develop much this approach, I would like to explore the possibility of understanding the wave/particle duality problem from this aristotalian notion. In *Physics*

22. Schrödinger, E.: Science and Humanism, Cambridge: Cambridge University Press, 1951, p. 121.

23. Schrödinger, E.: “Conceptual Models in Physics and their Philosophical Value” in Schrödinger, E.: Science, Theory and Man. London: George Allen and Unwin, 1957, pp. 149-150.

24. See Bitbol, M.: Schrödinger’s Philosophy of Quantum Mechanics. Dordrecht: Kluwer, 1996, pp. 167-171.

and Philosophy he suggests that most of the physicists regard the wave as some sort of potentiality, something not real at all, but as some kind of tendency:

> One might perhaps call it an objective tendency or possibility, a 'potentia' in the sense of Aristotelian philosophy. In fact, I believe that the language actually used by physicists when they speak about atomic events produces in their minds similar notions as the concept 'potentia'. So the physicists have gradually become accustomed to considering the electronic orbits, etc., not as reality but rather as a kind of 'potentia'[25].

The main question, then, would be to understand how we could consider the electronic orbits as not real, but just as possible tendencies. From a philosophical point of view this kind of "existence" or "possibility" should be clarified, because as Heisenberg also states:

> The probability wave of Bohr, Kramers, Slater… was a quantitative version of the old concept of "potentia" in Aristotelian philosophy. It introduced something standing in the middle between the idea of an event and the actual event, a strange kind of physical reality just in the middle between possibility and reality [26].

The only way of interpretating the wave function in a realistic way is by trying to understand a sort of reality that is not real at all, but just possible (or, we might say, a "real possibility"). In some sense the wave function is a wave of probability, but in another sense it is something real because it describes a real state of different possible states at the same time (superposition of states). The notion of "potentiality", as something intermediate between non-being and what is actual, seems to describe precisely the possible states in the wave function.

However, this Aristotelian notion of potentiality needs some clarification. For this reason it might be helpful to analyze some of Aristoteles' statements in books Θ and Λ of his *Metaphysics*. However, it is not the purpose of this essay to deal with possible problems of interpretation of this concept, but rather to grasp the main characteristics of this notion and then try to see if it could be helpful to understand quantum reality.

Aristotle develops his philosophy of potentiality in order to solve the problem of the sensible substance. One of the central questions of the ancient Greek philosophers was to know if we could say that the world we are living in is something 'real'. The great metaphysician Parmenides argued that taken the notion of 'being' seriously, it would be impossible to say that a world of change and motion could be said to be real: the world could be an appearance, but not something real. According to

25. Popper, K.: Quantum Theory and the Schism in Physics. Totowa: Rowman and Littlefield, 1982 (1956), pp. 199-200.

26. Heisenberg, W.: Physics and Philosophy. New York: Harper Perennial, 2007, pp. 154-155.

his metaphysical argumentation, there could only be one perfect being, without change or motion[27], because if there is change, there is some king of non-being state (for example, if the plant grows it is because it 'is not' completed at all). Aristotle tries to explain, against the strong parmenidian notion of being, that we can talk about being in different ways, that is, that there are different ways of using the word 'being'. Aristotle introduces his act and potentiality distinction in order to explain the way in which changes and motions of the world can be said to be real and also to explain one of the main characteristics of the physical world: that it is opened to new actualizations. In doing so in the *Metaphysics*, he argues against the strong Parmenidian vision of the world defended by the Megarian school, which denied all change and motion.

"There are several senses in which a thing may be said to 'be' (*to on legetai pollachos, Met*. 1028 a)"[28]. The first sense of being is the substance (*ousia*), taken as that what is subsistent along the time. We say that something is real because it is stable (and we could also say, because it is well defined in space and time). For this reason Aristotle says that we can say that bodies are substances, are real, because they are stable and well defined by their essence. The verb 'to be' must be applied first of all to this notion of substance, and therefore to other categories of being that are referred to the substance: "For it is in virtue of the concept of substance that the others also are said to be […]. And since 'being' (*to on*) is in one way distinguished into individual thing, quality and quantity, and is in another way distinguished in respect of potency (*dunamis*) and complete reality (*energeia*), and of function (*Met*. 1045 b)".

The primary sense of being must be applied to the substance, although it is possible to use the word 'being' in a different way when it is referred to what is actual or just potential. Aristotle develops this notion of potentiality as a way of explaining how it is possible that things that are real change in different ways, whereas that change is something also real. Aristotle defines potency as "a source of movement or change, which is in another thing than the thing moved or in the same *thing* qua other (*Met*. 1019 a 15)". The potency is the source of the movement because it brings a real capacity of actualization. It is a real capacity as a range of possibilities that can be actualized in only one way. For example, the healthy boy has the capacity of running, walking or cycling, but he is able to do just one activity at the same time. But, on the other hand, those possible activities are real possibilities grounded on the fact that the boy has healthy legs. Because the boy has a real potency of running, walking, cycling and so on,

27. Heisenberg, W.: Physics and Philosophy. New York: Harper Perennial, 2007, p. 15.

28. See Diels, H.-Kranz, W.: Die Fragmente der Vorsokratiker, Berlin, 1954, 18 B 6.

he is able to perform all those activities, but it will be impossible for him to perform all at the same time. When he is walking, he is not cycling.

For this reason Aristotle links the notion of potentiality with some kind of indetermination: “That which exists potentially and not in complete reality that is indeterminate (*aoristos*) (*Met*. 1007 b 27)”. Precisely because the potentiality is open to different actualizations, it is indetermined. Because the boy has healthy legs he has the capacity of performing different activities, but the fact of having legs (which is a real potentiality) does not determine him to do only one of them. That potentiality will be determined in some direction when the boy decides what to do with his legs and reaches some actualization.

The wave function could be undestood as some kind of potentiality in the sense that it is a source of movement and change (possible states) of the electron: the source of possible actualizations of the electron. This wave of possible actualizations is real in the sense that they are possible states with real effectiveness in the electron behaviour, although those possible states are being actualized in a determined way. The physical world is in some way actually determined, and that means that our knowledge of it will always be in a determined temporal and spatial position. Before the experiment the electron is in a state of potentiality towards its energetic manifestation. The wave function would express then the inherent potentiality of the quantum world.

According to Aristotle the potentiality is real, but not by itself: it needs a real subject or substance in which it can exist. For example, the potency of moving does not exist by itself, it exists in a real subject (the boy) that has that potency. However, the potency is real in the sense that it is a real property of potentiality (possibilites) that exists in a real subject. In this case the actual substance would be the electron (as a particle): before the measure there is a range spectrum of possibilities determined by the wave function. In this sense it would be easy to understand that the physical reality is not determined in a fixed way, because the potentiality we find in the quantum world provides the physical reality a range of possibilities without an absolute determination.

Moreover, it should be noticed that the wave function as potentiality should be understood in an active sense. The wave function is not the actual, but the potential: a sort of potentiality that tends to a proper actualization (See *Met*. 1021 a 15). But, as Aristotle notices, the potentiality only gets into the actual when something in act brings about the actualization. It would make sense, then, that we find the electron as a particle only in the energetic exchange, because it is when the exchange happens that something in act from outside brings the potentiality of the wave function into a determined actuality.

4. Heisenberg's use of the concept of potentiality

Having sketched the main features of the Aristotelian notion of potentiality, I will return to some of Heisenberg considerations and see how these notions can be applied to quantum mechanics. It must be noticed, however, that Heisenberg does not seem to apply this notion always in the same way: some times he follows a more realistic approach, while other times he seems to be close to a subjectivist view of the problem of measurement. We find a more realistic approach when he speaks of the probability as some kind of "objective reality":

"The most important of these [features of interpretation] was the introduction of the probability as a new kind of 'objective' physical reality. This probability concept is closely related to the concept of possibility, the 'potentia' of the natural philosophy of the ancients such as Aristotle; it is, to a certain extent, a transformation of the old 'potentia' concept from a qualitative to a quantitave idea"[29].

Heisenberg points out rightly that this interpretation of the probability in the wave function leads to a mathematical characterization of the concept of potentiality. The capacity of possible states has some kind of determination that is described precisely by the wave function in a mathematical way is expressed more precisely in the later text of Heisenberg's:

> The criticism of the Copenhagen interpretation of the quantum theory rests quite generally on the anxiety that, with this interpretation, the concept of 'objective reality' which forms the basis of classical physics might be driven out of physics. As we have here exhaustively shown, this anxiety is groundless, since the 'actual' plays the same decisive part in quantum theory as it does in classical physics. The Copenhagen interpretation is indeed based upon the existence of processes which can be simply described in terms of space and time, i.e. in terms of classical concepts, and which thus compose our 'reality' in the proper sense. If we attempt to penetrate behind this reality into the details of atomic events, the contours of this 'objectively real' would dissolve –not in the midst of a new and yet unclear idea of reality, but in the transparent clarity of a mathematics whose laws govern the possible and not the actual[30].

We are before a very interesting text that shows Heisenberg's philosophical position in regard to quantum physics. On the one hand, there is some approximation to Aristotle's notion of potentiality as a main cha-

29. Heisenberg, W.: "The Development of the Interpretation of the Quantum Theory" in Pauli, W.: Niels Bohr and the Development of Physics. Oxford: Pergamon, 1962, pp. 12-13.

30. Heisenberg, W.: "The Development of the Interpretation of the Quantum Theory" in Pauli, W.: Niels Bohr and the Development of Physics. Oxford: Pergamon, 1962, p. 28.

racteristic of the physical world, while on the other hand this potentiality reveals itself as a mathematical law that 'governs the possible'. In this sense, there is a curious mixture of Aristotelian and Platonic philosophy in his interpretation. However, the most interesting point of Heisenberg's statements lies in the link established between the notion of potentiality, as a source of indetermination, and the mathematical laws that rule that potentiality, as a source of knowledge of which way it can be determined. Returning to the example of the boy, the fact of having healthy legs gives him the capacity (potentiality) of doing different things but, on the other hand, his possibilities are restricted: he can walk, run, ride a bike, but he cannot fly. The potentiality is a source of indetermination directed towards determined actualizations. In this sense, the mathematical formalism describes the precise possible actualizations.

It must be noticed, nevertheless, that Heisenberg does not use this notion of potentiality always in the same sense. The potentiality/actuality description of the quantum world appears in his writings in some occasions as referred to the role of the observation and the collapse of the wave function:

> Therefore, the transition from the 'possible' to the 'actual' takes place during the act of observation. If we want to describe what happens in an atomic event, we have to realize that the word 'happens' can apply only to the observation, not to the state of affairs between two observations. It applies to the physical, not the psychical act of observation, and we may say that the transition from the 'possible' to the 'actual' takes place as soon as the interaction of the object with the measuring device, and thereby with the reast of the world, has come into play: it is connected with the act of registration of the result by the mind of the observer. The discontinuous change of our knowledge in the instant of registration that has its image in the discontinuous change of the probability function[31].

Whereas the wave function shows a probability of possible states, the fact of measuring makes a discontinuous change in that function, which is our actual and determined result in the experiment. It could seem that here "possible" and "actual" are referred just to our state of knowledge (probable/real), but I suppose that it could be possible to relate them to some intrinsic properties of reality. The "potential" and the "actual" are degrees of reality grounded on some kind of being, not just different kinds of knowledge.

In any case, from these statementes it is easy to understand why Heisenberg's position has often been interpreted as close to subjectivism. Some of his statements can be misleading, such as when he says: "The

31. Heisenberg, W.: Physics and Philosophy. New York: Harper Perennial, 2007, pp. 28-29.

electron path comes only into existence only when we observe it"[32]. Obviously the word "observing" can bring about confussion: it should not be understood as the subjective act of observing, but as the objective and real interaction that happens between the studied electron and the instrument of measurement. The "observation" is the experiment[33] that modifies the electron. It is due to this reason why Heisenberg can say that the electron path comes into existence when we observe it. Before any observation there is no energetic change, and the electron remains in its superposition of states, described by the wave function. Heisenberg's interpretation is a realistic position, though rather that a subjectivist one[34]. However, it seems that Heisenberg description of the wave function in terms of potentiality is an idea that he did not develop extensively[35].

5. Matter as source of indetermination

Quantum mechanics has offered us a way of understanding nature, and more precisely matter, as a source of indetermination in a very similar way as Aristotle defined the natural substance as composed by matter and form (potentiality and actuality). Matter in the aristotelian framework is precisely a principle or source of indetermination in nature:

> By matter I mean that which in itself is neither a particular thing nor of a certain quantity nor assigned to any other of the categories by which being is determined (*Met.*1029 a 20).

Aristotle defines matter as a basic substratum of reality, indetermined in itself as a principle of nature, although always determined actually with a specific form. Obviously we do not find this 'prime matter', and Aristotle would say that it is not real in itself, but only real as a basic principle inherent to the physical objects of the world. In other words: Aristotle notices that there is a principle of potentiality and indetermination in the physical world that allows something to change and to become something different than what it actually is. We find examples of this everywhere

32. Heisenberg, W.: "Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik" in Zeitschrift für Physik 43, 1927, p. 185.

33. See Heisenberg, W.: Physics and Philosophy. New York: Harper Perennial, 2007, p. 19.

34. See Hendry, J.: The Creation of Quantum Mechanics and the Bohr-Pauli Dialogue. Dordrecht: D. Reidel, 1984, p. 129.

35. Popper critizes Heisenberg precisely because after saying that the aristotelian potentiality could be useful to understand the wave function, he then goes on with the problem of the role of the observer and the problem of measurement introducing subjetivist elements in the interpretation. See Popper, K.: Quantum Theory and the Schism in Physics, Totowa: Rowman and Littlefield, 1982 (1956), pp. 132-133.

in nature: a stone is actually real, but there is a principle in the stone by which it can be turned into something else (a statue, dust, etc.): "All things produced either by nature or by art have matter; for each of them is capable both of being and of not being, and this capacity is the matter in each (*Met*. 1032 a 20)".

Matter is the inner capacity of every physical object of being or not being in a determined way. Matter is, in this sense, a principle a potentiality, just in the same way that the wave aspect of the electron is a source of possibilities and indetermination. If there is something that quatum mechanics has demonstrated in the last decades, it is the indetermined and potential character that appears in the most fundamental structures of the physical world. We find within the inner structure of matter a principle of indetermination and potentiality: possible actualizations grounded in the reality of the atom: that is what Aristotle would have called "potentialities", and what Popper calls "propensities". Which kind of reality do these potentialities have? Can we say that they are real in the same way that we say a house (located in a defined space and time) is real? This is not obviously the case, but it would make no sense to say that they are not, in some sense, real. They are real potentialities with real effectiveness, although this effectiveness is only revealed in its actual manifestations as particles. This notion of matter fits properly with the superposition of states of the wave function. As Aristotle says:

> The matter, then, which changes must be capable of both states. And since that which 'is' has two senses, we must say that everything changes from that which is potentially to that which is actually, for example from potentially white to actually white, and similarly in the case of increase and diminution (*Met*. 1069 b 14-20)

Matter is the potentiality of being two states, not at the same time, but as real possibilites that can become into the actual. It is because there is some source of indetermination and potentiality that things can become different from what they are, in as much as this potentiality is something real as potentiality: "The matter is that which is potentially each thing (*Met*. 1092 a 3). In other words: the most basic feature of matter (of being material) is the potentiality to become something else, to receive a different specific form:

> Sensible substance is changeable. Now if change proceeds from opposites as from intermediates […] there must be something underlying which changes into the contrary state; for the contraries do not change. Further, something persists, but the contrary does not persist; there is, then, some third thing besides the contraries, the matter (*Met*. 1069 b 1-8)

If natural things change from one state to another it must be due to a principle intrinsic to them that makes them changeable, that is to say, which gives them the potentiality of becoming something or in some aspect different of what they are. In this sense, it can be interesting to consider one of Heisenberg's statements concerning the way in which the notion of matter as a principle of potentiality can be applied to quantum physics:

> Actually the experiments have shown the complete mutability of matter. All the elementary particles can, at sufficiently high energies, be transmuted into other particles, or they can simply be created from kinetic energy and can be annihilated into energy, for instance into radiation. Therefore, we have here actually the final proof for the unity of matter. All the elementary particles are made of the same substance, which we may call energy or universal matter; they are just different forms in which matter can appear. If we compare this situation with the Aristotelian concepts of matter and form, we can say that the matter of Aristotle, which is mere 'potentia', should be compared to our concept of energy, which gets into actuality by means of the form, when the elementary particle is created[36].

Heisenberg points out that this prime matter can be considered as energy that capable of being transformed and specified in different ways. I think that Aristotle's concept of matter as a principle of potentiality can help to understand better some of the problems of interpretation of the wave function. It must be noticed, however, that this principle of potentiality and indetermination has to be adapted when applied to the wave function. In fact, there is no total indetermination in the wave function, but rather this superposition of states is described through mathematical formalities which indicate some kind of determination.

6. Popper's propensities as potentialities

The application of this notion of potentiality to quantum physics has also been defended in a slightly different way by Popper. Although Popper is opposed to Aristotelian metaphysics, which he views as "essentialist"[37], he offers an indeterministic interpretation not only of quantum mechanics, but also of classical physics, understanding by indeterminism "a doctrine asserting that not all events are 'determined in every detail'"[38]. In this sense, he does not

36. Heisenberg, W.: Physics and Philosophy. New York: Harper Perennial, 2007, p. 134.

37. Popper, K,: The Open Society and its Enemies. Vol. I. The Spell of Plato. London: Routledge, 1945, p. 25.

38. Popper, K.: "Indeterminism in Quantum Physics" in British Journal for the Philosophy of Science 1, 1950, p. 120.

state that everything in nature is indetermined, but rather that there can be some events that are not completely determined.

In fact, Popper's indeterministic view is a realistic interpretation of quantum mechanics in which he defines the probabilistic character of the wave function as something real, precisely in what he calls "propensities".

"I believe that the quantum theory is in a very definite sense a particle theory (here I disagree with Schrödinger) and in a sense which excludes a duality, or analogy, or complementarity, between particles and waves. To be more explicit, I believe that the waves (even those of the second quantization) are mathematical representations of *propensities*, or of dispositional properties, of the physical situation (such as the experimental set-up), interpretable as propensities of the *particles* to take up certain states"[39].

Popper develops a realistic view of quantum mechanics: particles are real, and the formalism of the equations describes possible values of the variables of the system:

> The particles do not appear, explicitly, in the formalism –neither in the wave formalism, nor in the matrix formalism (…). All these theories describe the propensities of certain variables to take up certain values; variables that may be interpreted as variables of the state of certain particles[40].

The theory, then, describes some relational values as possible states[41]. But what are, then, the waves described by the formalism? Are they something real? Popper states that they must be understood as something real in the sense that they are propensities of the system: real relational properties that can be measured as possibilities. In this sense, I think that Popper's philosophy of propensities does not differ too much from the use that Heisenberg makes of potentialities, but here we find a more developed metaphysical account in a clear realistic way.

Popper's account of propensities integrates the wave function into the realm of reality as a real possible range of states and values of the electron. But, which kind of reality are these propensities? They are real in as much as

39. Popper, K.: Quantum Theory and the Schism in Physics. Totowa: Rowman and Littlefield, 1982 (1956), p. 126.

40. Popper, K.: Quantum Theory and the Schism in Physics. Totowa: Rowman and Littlefield, 1982 (1956), p. 127.

41. In fact, it seems that the formalism of the theory does not have a descriptive character, but rather a dispositional one: it calculates the disposition of the system to show certain values. See Hughes, R. I. G.: The Structure and Interpretation of Quantum Mechanics. Cambridge: Harvard Univesity Press, 1989, pp. 68-69.

they are real possibilities, which, as far as I can see, is the same as to say that they are potentialities in the way described by Aristotle:

> We thus obtain a picture of the world which is at once dualistic and monistic. It is dualistic in that the potentialities are potentialities only relative to their possible realizations or actualizations; and it is monistic in that the realizations or actualizations not only determine potentialities, but may even be said to be potentialities themselves. (But we should perhaps avoid saying that they are 'nothing but' potentialities). Thus we may describe the physical world as consisting of changing propensities for change[42].

Both Heisenberg and Popper understand that there is some kind of potentiality inherent to the quantum world. Heisenberg speaks of this potentiality as "the possible", whereas Popper's doctrine of "propensities" seems to attribute a more physical reality to this potentiality. In fact, Heisenberg's distinction between the possible (potentiality) and the real (actuality) can lead to a subjectivistic interpretation of quantum mechanics. The fact that the inherent potentiality of the quantum world is described in terms of mathematical wave functions is seen by him as a victory of the platonic philosophy (geometrical description of the world) over the materialistic and deterministic vision[43].

7. Chance and indetermination

One of the main problems for accepting the probabilistic account of the wave function is that it seems to bring chance into the physical world. Precisely because there is not a deterministic causal connection between the possible states that describe the wave function and the actual state that appears in the measurement process, it would seem that it is a mere question of chance that the electron behaves in one or onother way.

Nevertheless, it is necessary to be accurate with the terms "chance" and "indetermination" in order to avoid misinterpretations. By the word "chance" we understand something that is opposed to "causality", complete randomness. It is clear that there is not such complete randomness in quantum mechanics, and it would be inappropriate to say that there is chance. In fact, if there is chance one would have to hold that it is governed by some rules[44], so it would

42. Popper, K.: Quantum Theory and the Schism in Physics. Totowa: Rowman and Littlefield, 1982 (1956), p. 160.

43. "I think that on this point modern physics has definitely decided for Plato. For the smallest units of matter are in fact not physical objects in the ordinary sense of the word; they are forms, structures or –in Plato's sense– Ideas, which can be ambiguously spoken of only in the language of mathematics. Democritus and Plato both had hoped that in the smallest units of matter they would be approaching the 'one', the unitary principle that governs the course of the world. Plato was convinced that this principle can be expressed and understood only in mathematical form. Heissenberg, W.: Across the Frontiers. New York: Harper & Row, 1974, p. 116. See also Heisenberg, W.: Physics and Beyond. New York: Harper & Row, 1971, pp. 11-12.

44. See Born, M.: *Natural Philosophy of Cause and Chance*. Oxford: Clarendon Press, 1949, pp. 3-4.

be better therefore just to speak of some kind of indetermination in the way matter obeys these rules. In this sense, there is causality in quantum mechanics, although not absolute determination.

Aristotle's concept of matter as a principle of potentiality did not refer to a physical sense of indetermination, but was rather a metaphysical tool used to explain why every material object can become something different from that what it actually is: there must be a principle which is not completely determined by the actual form. One could think, however, that this concept of matter as a principle of indetermination could have a physical ground based on the fact that there is some indetermination in the behaviour of the quantum particles. In this sense, it would be possible to say that main feature of being material is precisely not being at all determined. I think that Popper's account on propensities arrives at a similar solution which allows an understanding of how indetermination fits in a real world of potentialities:

> The tendency of statistical averages to remain stable if the conditions remain stable is one of the msot remarkable characteristics of our universe. It can be explained, I hold, only by the propensity theory; by the theory that there exist weighted possibilities which are *more than mere possibilities*, but tendencies or propensities to become real: tendencies or propensities to realize themselves which are inherent in all possibilities in various degrees and which are something like forces that keep statistics stable. This is an *objective interpretation of the theory of probability*. Propensities, it is assumed, are not mere possibilities but are physical realities. They are as real as forces, or fields of forces[45].

Thus, the wave function could be interpreted from a philosophical point of view as the mathematical configuration of the proper potentialities of the electron. Actual reality is always presented to the human mind in a determined space-time configuration. In this sense, it is not possible to imagine how the wave function is determined in a normal space-time configuration, because it is just a source of potentialities that only becomes actual with some kind of energetic manifestation. While electrons become actual in their energetic manifestations, it should be interpreted as an indetermined potentiality before any exchange of energy takes place. It should be added, nevertheless, that there is no complete indermination, because it is configured through the mathematical formalism of the wave function. While on the one hand it is a potentiality determined by possible configurations, on the other hand it is indetermined and open to different actualizations. At this point I agree with Popper's account of the propensities: "In the terminology of Aristotle we might

45. Popper, K.: A World of Propensities. Bristol: Thoemes, 1990, p. 12.

say: ‘To be is both to be the actualization of a prior propensity to become, and to be a propensity to become’”[46].

8. Conclusions

In the previous pages I have tried to offer a realistic account of quantum mechanics based on metaphysical notions developed by Aristotle in connection with Heisenberg’s and Popper’s views. It should be noted however that Heisenberg’s and Popper’s views of the natural world are quite far away from Aristotle: the main reason is because their main goal is to overcome the Newtonian physical deterministic model, and they do it from the discoveries of the quantum world. Even though, I have tried to show how the Aristotelian notion of potentiality seems to be in agreement at some points with these thinkers. With this interpretation I am not offering a scientific tool, but rather a more comprehensive approach in order to understand what is nature. I think that these kinds of comprehensive approaches are necessary if we want to admit that science describes something real about the world. Quantum mechanics has offered us a mathematical formalism to describe the main structures of matter. Beyond the questions raised it also shows us that in the depths of the atom matter is revealed as a source of indetermination and potentiality. The philosophical problems that arise from quantum mechanics force us to look for ways of understanding in which way can we say that the particles and the waves are real. Perhaps, what quantum mechanics has shown to philosophy is that the old Greek questions related to change and stability remain unsolved.

46. Popper, K.: Quantum Theory and the Schism in Physics. Totowa: Rowman and Littlefield, 1982 (1956), p. 205.