METAPHYSICS OF QUANTUM MECHANICS: USEFUL OR A STERILE INTELLECTUAL EXERCISE?

LUIS A. DE VEDIA

Starting to solve the riddle

The search for a realistic interpretation of Quantum Mechanics (QM) is still the subject of a heated debate that is taking place on the border between science and metaphysics and that dates back to the famous Einstein-Bohr debate in the 1930s. This debate had its culminating expression in the work published in 1935 by Einstein with his Princeton collaborators, Boris Podolsky and Nathan Rosen[1], in which he argued that the Copenhagen interpretation was incorrect and that in fact there was some underlying mechanism that only gave the appearance of uncertainty and unpredictability at the quantum level. These authors suggested imagining two initially close particles interacting with each other and then moving away from each other without interacting with anything else until the experimenter decides to act on one of them. Each particle has, according to the authors, its momentum and its position in space. Even within the rules of the QM it is possible to accurately measure the total momentum of the two particles when they are still close. When it is later decided to measure the momentum of one of the particles, say that of particle A. Without having acted in any way on particle B, we know its momentum, since we had information on the initial total momentum that must have been kept constant. So particle B must have had, at the time of measurement on particle A, that momentum. Alternatively, it could have been decided to measure the position of particle A and thus, also indirectly, know the position of particle B without disturbing it and since no action had been taken on particle B in any way, it should have had that position. So uniting the measurement that was carried out with the one that could have been carried out, the authors concluded that particle B has a definite position and momentum at all times. Of course, this analysis can be performed by swapping the particles whereby both particles would always have a defined position and momentum. This was known as the EPR paradox.

It was the physicist David Bohm[2] who reasoned that the EPR paradox could be formulated in terms of whether the particles possess a defined spin on one or on all the axes. For the purposes of the considerations that follow, it is only necessary to take into account that the "*spin*" of a micro-entity such as an electron, a neutron or a photon, is a property represented by a non-classical variable and that as such cannot be expressed in terms of concepts of classical physics. This does not prevent the use of an analogy between the spin of a particle and the intrinsic angular momentum of a classical particle that rotates on its own axis. Both the spin and the intrinsic angular momentum can be represented by a vector with magnitude and direction. However, and this constitutes a fundamental difference between the classical intrinsic angular momentum and the spin, the first one has a component with defined value for any direction in which it is measured, and knowing this value, the value of the intrinsic angular momentum that will vary continuously between a maximum and zero can be predicted with exactitude for different directions. Instead, chosen an arbitrary direction, the spin can

[1] Einstein, A.; Podolsky, B.; Rosen, N. ""*Can quantum mechanical description of physical reality be complete?*" Physical Review, **47**, 777, 1935.

[2] Bohm, D. "*Quantum Theory*" Prentice Hall, Englewood Cliffs, NJ, 1951.

only adopt two fixed values, which are usually referred to as "*spin up*" or "*spin down*", and the determination of the spin for that arbitrary direction makes it impossible to accurately predict the spin value along some other direction, only *the probability* that the result of a measurement for that other direction being "*spin up*" or "*spin down*" can be calculated.

Now, Bohm imagined two detectors capable of measuring the spin of an incoming electron, located at opposite ends of a laboratory. Two electrons are prepared so that their spins are initially correlated so that when separated and entering each electron to the corresponding detector, having both detectors adjusted to measure the spin in the same direction, both detectors will give the same result (spin "up" or spin "down"). Now, QM only allows predicting the probability that both detectors measure one or the other result. What we have in this case is the certainty that both detectors will give the same result. As in the EPR paradox, the measurement of the spin of one of the electrons by a detector indirectly gives us the spin information of the other electron on the same axis. Since this electron has not been acted on in any way, it must have had this spin on that axis. Since these measurements could have been made on any axis, the conclusion arises that this electron has a defined spin on any axis. From the above it appears then that an electron would have spin defined on any axis. But the Principle of Uncertainty makes it impossible to simultaneously measure the spin in more than one direction. It can be questioned here the meaning of talking about the existence of something that cannot be determined.

The dilemma introduced by the EPR paradox belonged to the field of metaphysics until the conceptual overturn produced by the work of the Irish physicist John Bell of CERN [3] in 1964 giving rise to the "*Bell inequality*"[4] that enables for the first time the possibility of using an experimental methodology to resolve the dilemma introduced by the EPR paradox. Indeed, Bell realized that although it is not possible to measure the spin of a particle over more than one direction, if the particle has a spin defined over all directions, there are experimentally confirmed consequences. A consequence of Bell's Theorem is that if EPR were correct, two spatially separated detectors measuring in randomly selected directions the spin of initially correlated particles should coincide in their results more than 50% of the time.

At the time Bell obtained this result, the technology was not yet available to confirm it. The crucial experience was that carried out by Aspect and his team in France in 1980. In this experiment, two detectors were placed at a distance of 13 m from each other with a container of calcium energy atoms at the midpoint between both detectors. When moving to a state of lower energy, a calcium atom emits two photons in opposite directions with their correlated spins. So in this experiment, if the detectors are set in the same direction, the spins of both photons will produce the same result (both spin "up" or both spin "down"). But when the direction of the detectors was varied independently at random in each measurement, the detectors did not coincide in their results in more than 50% of the cases, which refuted the theory of hidden variables. To see that this is indeed so, let us assume that by means of the two detectors we can measure in the directions x, y, z, the spin of the initially correlated photons. We know that if the measurement S_{z1} results in spin "up" or spin "down", the measurement S_{z2} will give the same result spin "up" or spin "down" and analogously with the measurements S_{x1} and S_{y1} in relation to the measurements S_{x2} and S_{y2}. Now, according to Einstein and his collaborators, each pair of photons carries with it the same "*program*" written in terms of hidden variables, which determines the value of each measurement according to the axes x, y, z. Suppose that this program determines that the results of the measurements of

[3] CERN: European Center for Nuclear Research, near Geneva, Switzerland.
[4] Bell, J.S. "On the problem of hidden variables in quantum mechanics"

the detectors according to these axes are respectively: spin "up", spin "up", spin "down"

So the combinations that will yield matching results will be (S_{x1}, S_{x2}), (S_{y1}, S_{y2}), (S_{z1}, S_{z2}), (S_{x1}, S_{y2}), (S_{y1}, S_{x2}), that is they are five combinations in total. The possible combinations of directions are instead *xx, xy, xz, and x, yy, yz, zx, zy, zz*, that is to say nine in total. Given that five is more than half of nine, the validity of the theory of hidden variables would imply that in a sufficiently large number of measurements made on the *x, y, z* axes independently randomly by each detector, we would have to find coincidences in the pairs of measurements more than 50% of the time what is not verified experimentally. Although in this analysis we have considered the particular "program" spin "up", spin "up", spin "down" for the directions *x, y, z*, respectively, any other program would yield the same conclusions and the same should be stated if instead of considering measurements according to three defined directions, any directions would have been considered. This implies that the probability of the result of a subsequent measurement of any other component of the spin of the second particle will have changed as a consequence of the first measurement, even though the particles are spatially separated by an arbitrary distance and without apparent interaction between them.

The experimental refutation of the theory of hidden variables leads us to the anti-intuitive conclusion that in quantum phenomena, spatial locality does not seem to be fulfilled and a kind of instantaneous action at distance is revealed. In addition, the absence of hidden variables introduces an essential indeterminism in what makes the result of measurements of dynamic variables in general. This non-local character of QM is already evident in the experience of electron diffraction through slits, where the diffraction spectrum occurs even when the electrons enter the device one at a time. This means that the electron somehow "*passes*" through both slits which prevents it from being considered a localized particle. This non-localization of the particle is interpreted to some extent by the wave aspect associated with the electron. In relation to this, it is important to remember that this wave aspect disappears at the moment in which a detection of the position of the electron is made, for example at the exit of one of the slits. This simple experience reveals the so-called measurement problem in QM and which we can describe as follows: let's assume that we have a *q-system*, as an electron that we have prepared in such a way that we know its initial spin, that is, for $t = 0$, let's say spin "up". This means that if we immediately made a new measurement of the spin in the same direction, we would obtain the same result. Now, the wave function of the electron in this state is such that the spin operator has an eigenvector with an eigenvalue in the measurement direction of the measured spin value, in this case spin "up". From the moment in which the measurement of the spin ($t = 0$) is made, the evolution of the state of the electron in its subsequent interaction with possible electric and magnetic fields is totally determined by the evolution of its wave function according to the Schrödinger equation . This evolution, totally deterministic, is maintained until a new measurement is made. The result of this new measurement cannot be predicted in an exact way and all that we can infer from the knowledge of the wave function using the operator corresponding to the direction selected to carry out the new measurement, is the probability that the result will be spin "up" or spin "down".

In other words, the measurement of a dynamic variable "*destroys*" the information that was available about the state of the *q-system* through the deterministic time evolution of its wave function and "*jumps*" into a new state corresponding to the eigenvector of the operator of the dynamic variable under consideration. This "*jump*" from a perfectly deterministic time evolution to a defined but random result state when a measurement is made is what is known as "*reduction*" or "*collapse*" of the wave function. It is important to highlight here a terminological question to avoid confusion. Indeed, unlike the usual terminology in the different philosophical positions with respect to the reality, the dynamic variables in QM are called *observables* although they are only determinable from measurement instruments, which would qualify them, according with those positions, as unobservables.

A point to note about the probabilistic interpretation of the results of a measurement in QM, is that unlike the usual interpretation on the probability of obtaining a given result as it could be the random extraction of a number of the lottery in which the balls with the different numbers have real existence before the extraction, in a *q-system*, until the moment of making the measurement, the dynamic variable to measure does not have, according to the orthodox interpretation, a definite value, which it only acquires when the reduction of the wave function by the measurement act is produced. For this reason we say above that the *q-systems* are according to QM in a sort of probabilistic limbo, from which they only emerge when the act of measurement is made.

The question that arises in relation to the phenomenon of wave reduction is at which stage of the measurement process the reduction occurs. It can be argued that the reduction occurs at the moment in which the experimenter obtains the information of the observable value through the reading of a measurement instrument whose operation is described in classical terms. But the boundary between the deterministic evolution of the system according to the Schrödinger equation and the state corresponding to a definite value of the measured observable is mobile and could be located at any point between the *q-system* and the observer. Indeed, the interaction between the *q-system* and at least part of the measurement instrument can be described in quantum terms, so it is not clear at what point of the entire measurement process the collapse or reduction of the wave function occurs resulting in a defined result for the measured variable. If all the physical systems, even the classical ones, as the instruments of measurement are, can be described with the quantum formalism beyond the mathematical difficulties, and QM assures that this is indeed so, how can there be place for instruments whose measurements correspond to states described in classical terms?

The answer given by Bohr is that experimental scientists design, perform, interpret and communicate the results of their experiments in terms of classical physics. We understand how macroscopic instruments work only in terms of classical concepts. The effect of an event that occurs at the level of an individual quantum particle must be amplified in some way, that is transformed into some kind of macroscopic signal so that it can be perceived and measured. Our perception works at the level of classical physics and the only concepts with which we are familiar and for which we have a highly developed language are the classical concepts. The theory is thus only an instrument whose purpose is to provide correlations between the state of a *q-system* and a process (of measurement) that prepares the system in a given quantum state for the subsequent measurement of the observable, so that according to Bohr, there exists an essential inseparability between the quantum system and the measuring device. However, this position is debatable given the results that show that the probability of obtaining a given value of an observable in a q-system A through a complex measurement instrument B + C, is the same as considering the A + B system and performing the measurement with instrument C. In other words, the inseparability of metaphysical nature that according to Bohr is between the *q-system* and the classical instrument of measurement remains unsolved.

These difficulties have led some scientists, in particular E. Wigner[5], to suggest that the collapse of the wave function occurs only when a conscious mind becomes aware of the value of

[5] Wigner, E. "*Remarks on the mind-body question*" In "*The scientist speculates: an anthology of partly-baked ideas*" Ed. I.J.Good, Heinemann, London, 1961.

the measured observable. It is not surprising that this position of a dualistic metaphysics of a physical world on the one hand and conscious minds on the other has few adherents. Its critics, on the other hand, argue that the collapse of the wave function caused by the intervention of a conscious mind remains unexplained and outside the competence of physics.

A more promising alternative is the characterization of the measurement process as a particular kind of physical interaction involving a microsystem (the *q-system*) and a macroscopic system (the measurement instrument). In this way, a microscopic aspect of the system that is measured correlates with macroscopic aspects of the measurement system in a way that reveals the value of the microentity. For example, in an operation in which a detection is performed to know through which slit the electron passes, this detection can be performed by a device that amplifies the effect of the passage of the particle through the detector, for example by a cascaded amplifier that multiplies the number of charged particles that end up revealing the presence of the initial microentity through a macroscopic voltage produced by a large quantity of charged particles acting in concert. Bear in mind that there are two characteristics in the measurement process: the first is that the state of the measuring device always involves a large number of particles and is characterized in a macroscopic scale. The second is that the final state of the apparatus is macroscopically discernible, that is, it is not a state of superposition but a "*pure*" state but perfectly correlated with the possible quantum states of the system being measured.

The adherents to this interpretation of the measurement process accept, however, that the interaction between the quantum microsystem and the measurement instrument obeys the laws of QM. This implies that if the microsystem to be measured is in a state of superposition, for example spin "*up*" with spin "*down*" the system constituted by the microsystem and the measuring device must also be in a state of superposition spin "*up*" and spin "*down*" plus the instrument indicating, say, spin "*down*". What happens is that since the measuring device is macroscopic, it is constituted by an enormous quantity of particles, so the characterization of its state requires a great amount of degrees of freedom. The effects of interference between the microsystem and the instrument do not disappear completely, but they dissipate in the amplification process from which only a value of the measured dynamic variable emerges, in this case spin "*up*" or spin "*down*", which is taken as the value of the measurement. This phenomenon by which those components of the wave vector of the *q-system/measuring apparatus* that are in superposition are destroyed quickly, is called *decoherence* and is responsible for not normally observe interference phenomena at the macroscopic level.

So, according to this interpretation, the collapse of the wave function must be interpreted as the result of the complex interaction between the microsystem and the measurement device (plus the external environment), which makes the effect of superposition between the two in practice undetectable. Only the possible macroscopic states of the measuring device are detectable. This decoupling of the components of the wave vector that are in superposition is the result of the coupling of the wave vector to the innumerable states of the measuring device and its environment. The phenomenon that can be taken as analog in classical physics is the dissipation of energy through friction or viscous damping phenomena. However, the analogy should not be taken too far since the decoherence must be completed on a much shorter time scale than the one usually taken by the energy dissipation phenomenon. So the coherence or superposition of states that represents a state vector is an extremely labile condition. The interaction of the wave vector with just a few photons or atoms is enough for the decoherence of its superimposed components to take place quickly and the quantum system acquires a classic characteristic. It is noteworthy that this process of projection of the wave vector in a given state is not instantaneous as it is posited by the orthodox QM, but rather it is a physical process that requires some time to complete.

The theory of decoherence has already been incorporated into the mainstream of physics research and tells us that the transition between a delocalized quantum object and a localized classical object can be related to a decoherence factor $e^{-t/\tau}$, where τ is the time of decoherence This decoherence time is related to the size of the object under study and the number of interacting particles in its environment. The smaller τ, the shorter the time it will take for the state vector to eliminate its superimposed components and become, together with the measuring device and its environment, a classic object. Thus, there are calculations that allow estimating that a molecule of radius about 10^{-6} cm, moving in the air, has a decoherence time of approximately 10^{-30} s. By eliminating the air, that is to say in a laboratory vacuum, the same molecule would have a decoherence time of about 10^{-17} s. In the intergalactic space, in which the molecule would interact only with the background radiation, the decoherence time would increase to about 10^{12} s, which means that the molecule could remain in a delocalized state for just under 32,000 years[6]! In contrast, a dust particle will manifest itself as a classical object even when the interaction with the environment remains low. In the experience of electron diffraction through slits, the electrons that pass through the apparatus are maintained in a delocalized state represented by the vector or wave function until the interaction of that wave vector with the multitude of atoms that constitute the photographic plate so the decoherence time becomes extremely short and for practical purposes we can consider it as an instantaneous event in which the electron appears as a spot in a defined place on the plate. In relation to this, it is necessary to ask how it is possible to observe macroscopic phenomena of interference in our daily life (for example the interference colors in an oil stain on the floor). The answer is that in these cases the agents responsible for the phenomena are photons and quantum electrodynamics teaches us that the interaction between them is practically nil, so the interference lasts and we can observe its effects at the macroscopic level.

The theory of decoherence makes it possible to explain why Schrödinger's cat is alive or dead and not partially alive and partially dead. However, it does not eliminate another aspect of QM that conspires against a realistic interpretation of it. This aspect is its probabilistic nature, that is, its indeterminism. Some of the difficulties associated with the non-local indeterministic nature of QM can be reduced by the traditional (Copenhagen) interpretation complemented by the interpretation just discussed. In effect, both emphasize the role of measurement instruments as an integral part of any experiment with a *q-system*. From this point of view, the result of a measurement, for example of a spin component of one member of a correlated pair of particles, must be seen as a property not only of the particle but of the entire system including the other member of the correlated pair and the set of measuring devices, so that the subsequent correlations should be interpreted as correlations between the properties of the particles plus the properly oriented devices and not as properties of the particles exclusively. In this way, until the first measurement is made, the system would not be considered to be constituted by two separate particles and therefore it is reasonable to expect that after this first measurement the properties of the entire system have been modified. It is not necessary to think of particles as influencing each other non-locally since they have no independent existence prior to the time of the first measurement. Note that this interpretation reduces in some way the problem of non-locality but not that of indeterminism, since although it does not make it necessary to resort to metaphysical arguments as it can be the role attributed to the

---

[6] These estimates correspond to Omnès, R. "*The Interpretation of Quantum Mechanics*" Princeton University Press, Princeton, NJ, 1994, and are cited by Baggott, J. in "*Beyond Measure*" Oxford University Press, 2004.

intervention of a conscious mind, the reduction of the wave function with its random results is still present. An advantage of the previous interpretation is that the entire measurement process is explained as a result of the physical interaction between the microsystem and the measurement instrument.

To the rescue of realism.

We have seen then that in the orthodox interpretation of QM, the aspects that conspire against the adoption of a realistic position for the theory and for the entities that it postulates, are fundamentally the non-locality of the quantum phenomena and the collapse or reduction of the wave function that gives rise to an irreducible indeterminism when a measurement is made. The latter is true except in the particular case in which the system has been prepared previously in an eigenstate of the dynamic variable to be measured (for example by making a previous measurement), in which case, if the system evolves in isolation, i.e. without interacting with other systems, it is certain that the result of a new measurement on the same variable, will yield the same result as the previous measurement and will correspond to the eigenvalue of the eigenstate in which the microsystem is. In any case, in general, the systems will not be found in the operator's eigenstate corresponding to the dynamic variable to be measured.

The spatial-temporal locality of causal relationships and determinism are two classic attributes that have always been considered must exhibit any phenomenon so that it can be considered real. These attributes are precisely those that are questioned in the orthodox interpretation of QM and it is what introduces a questioning about the reality of the entities that QM postulates, such as electrons and other microentities. Because of this, we can say that QM in its orthodox interpretation does not refer to what it is, but to what will happen when we observe a system and this prediction has in general an essentially probabilistic character. Indeed, if in classical mechanics the calculation allows us to predict that a particle will be in position x at time t, we know that if at that moment we made an observation at that point, we would find the particle. In QM, a particle, say an electron, will be represented by a vector or wave function $\psi(x, t)$ that depends on the position x [7] and of time t. Now, QM teaches us that the probability of finding the electron when we make an observation in the region limited by the interval Δx, is $|\psi(x, t)|^2 \Delta x$, that is, there is a finite probability of finding the electron in any region of space where the wave function is not canceled. In other words, the electron is delocalised unlike what happens with a classical particle. The act of observation is what causes the electron, until that moment to be delocalised, to transform into a specific particle of localization defined as a consequence of the reduction of the wave function induced by the act of measurement. This phenomenon of reduction or collapse of the wave function is undoubtedly one of the most intriguing of QM and is at the very basis of speculations about the reality of the quantum world.

Another manifestation of the non-locality of quantum systems is obtained when we consider, as we have seen above, a system constituted by two particles that are somehow correlated (for example, by having zero total spin, or something similar). In this case, the system wave function $\psi(x_1, x_2, t)$ will depend on the positions x_1, x_2 of both particles and time t. The "*object*" represented by this wave function is certainly peculiar given that the probability of finding one of the particles in a given position depends on the position of the other particle, however far away it may be, which suggests a strange instantaneous action at a distance between both

[7] For simplicity, we are considering a one-dimensional system.

particles that is sometimes called "*spooky action at a distance*".

We have already mentioned that this strange action at a distance, which is not only strange but would violate one of the two fundamental postulates of special relativity that establishes the speed of light in a vacuum as a limit impossible to overcome by any physical entity, it can be eliminated or at least attenuated if we consider that up to the moment in which the first measurement is made, the system is not constituted by two independent particles but by two entities correlated in some way. In fact, the mathematical form $\psi\ (x_1, x_2, t)$ of the system wave function is telling us that the system is described at each instant by a probability distribution that is a function of both variables x_1 and x_2. Perhaps the difficulty in assigning real existence to this entity comes from our daily experience that attributes to the events that we see happening in the world a spatial-temporal locality, since even those events that extend in time and space, they can always be reduced to a causal chain, in which each cause-effect link has spatial-temporal contiguity with the next. However, reality may be much stranger to our intuition than we assume, which would lead us to accept that a quantum system can represent a whole even if it exists in a spatially and temporally delocalized way. According to this idea, the disturbance suffered by one of the particles at the moment in which a measurement is made on the other, does not imply the transmission of a superluminal signal but is a modification of the state of the system, which until that moment is a whole, since you cannot speak of "*parts*" of the system.

In any case, as we have already mentioned, the previous interpretation combined with the theory of decoherence, although it allows us to reduce or do without the need for remote action and explain the collapse of the wave function, does not eliminate the probabilistic character of the predictions of the theory. The experimental verifications of the Bell Theorem carried out to date, seem to demonstrate with reasonable force the impossibility of a local QM of hidden variables, which does not prevent conceiving a nonlocal theory of hidden variables. Several ideas have been developed on this aspect, but we will only refer to the two that have generated the most acceptance (perhaps it would be more appropriate to say that they are the ones that have been rejected less by the community of physicists). Because they are of hidden variables, both theories are "*realistic*", that is, they do not question the objective existence of the entities they postulate.

These theories are: the de Broglie-Bohm[8] theory and that of multiple worlds of Everett[9]. De Broglie-Bohm's theory recognizes as an antecedent the idea of a pilot wave proposed by Louis de Broglie in 1926. This idea consisted in assuming that quantum entities, such as electrons, photons, etc., are actually real particles that move in a real field of forces. This field of forces, however, has the same statistical significance as the Schrödinger wave equation and leads to the same probabilistic interpretation. This means that the particles would follow a path defined by this field of forces or pilot wave that guides the particles along the most likely path that is the one in which the amplitude of the pilot wave is greater. Thus, the probability of finding the particle in one place remains proportional to the square of the amplitude of the pilot wave at that point as in orthodox QM, but now the particle is real and is located at all times.

In the experience of electron diffraction through slits, the pilot wave is the one that diffracts

---

[8] Bohm, D. "*A suggested interpretation of the quantum theory in terms of "hidden" variables*" I and II, Physical Review, **85**, 166, 1952.
[9] Everett III, H. "*'Relative state' formulation of quantum mechanics*" Reviews of Modern Physics, **29**, 454, 1957.

and produces the interference phenomenon giving rise to a pattern of alternating zones of high and low amplitude. The electron is guided by this field and therefore has a greater probability of ending in a region where the field of forces has greater amplitude, so that the arrival of many electrons will form the known diffraction spectrum, for example on a photographic plate. Note that unlike Bohr's interpretation, according to which electrons behave as waves or as particles, in de Broglie's scheme electrons are always localized particles accompanying a force field that is always a wave. So this theory is effectively of hidden variables, in which the hidden variable is not the pilot wave but the positions of the particle that are those that remain hidden. Note that the theory of the pilot wave reintroduces the concept of causality, since the particles follow at all times a classic path determined by a force field but does not eliminate non-locality or remote action when the system is constituted by two or more correlated particles.

The 1952 Bohm modification of the de Broglie pilot wave theory implies the reinterpretation of the Schrödinger wave equation as representing a field of objective real existence and its reformulation in a way similar to the fundamental equations of Newtonian dynamics This equation of motion depends not only on the classical potential but also introduces a second potential called quantum potential. To illustrate this idea a bit, let us mention that the quantum potential takes the form

$$U = \frac{1}{2m} \mathrm{Re} \left\{ \frac{p^2 \psi}{\psi} - mv^2 \right\} \qquad \textbf{(10. 1)}$$

where Re denotes the real part of the complex expression in parentheses and p is the quantum operator momentum that acts on the wave function. The equation of motion in the de Broglie-Bohm theory is then

$$m \frac{dv}{dt} = -\frac{\partial V}{\partial x} - \frac{\partial U}{\partial x} \qquad \textbf{(10. 2)}$$

where V is the usual scalar potential and v the velocity of the particle. We see here that when the quantum potential is canceled, the previous equation reduces to the 2nd Newton law. This quantum potential is responsible for the introduction of quantum effects into a description that is otherwise classical and can exert effects in regions where the classical potential disappears (or remains constant). In this way, a particle that moves in a region where the classical potential is null or constant may not follow a straight path as dictated by classical mechanics, which allows us to explain, for example, within the framework of this theory, the motion of the electrons in the slit diffraction experience, as shown in the figure on the right.

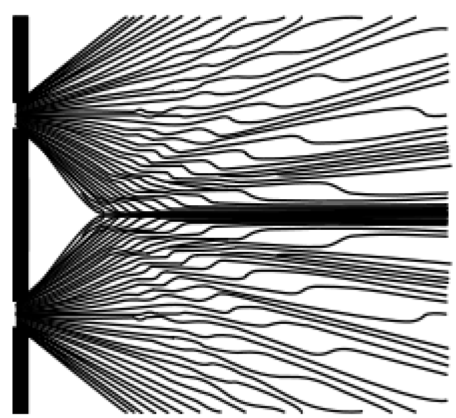

Fig. 1 - Trajectory of an electron passing through a device with two slits, calculated using the quantum potential. Note the alternate presence of areas with higher trajectory densities

So that the position and trajectory of the particles are always perfectly defined and in the de Broglie-Bohm's theory it is not in principle necessary to resort to probabilistic concepts. In this theory, the particles have a perfectly defined position and moment, however, since in general the initial conditions are not completely known, it is necessary to resort to the probabilities as a practical resource analogous to their use in statistical mechanics. When the particles have a perfectly determined position and trajectory, the act of measurement only reveals that position or trajectory and does not have the protagonist connotation assigned by the orthodox QM. Despite its determinism, the de Broglie-Bohm's theory does not generate conflict with the Heisemberg's Uncertainty Principle but modifies its interpretation.

Indeed, according to this theory, although the position and momentum of the particle are defined, the act of measuring one of the variables (for example the position) has an impact on the wave function and therefore on the quantum potential that then affects the other variable (in this case the momentum), which is in line with the Principle of Uncertainty. So the de Broglie-Bohm's theory provides us with a realistic deterministic interpretation but maintaining the non-locality of quantum phenomena. There are, however, several objections that can be raised against this theory. One of them is that the guiding wave can exert a strong influence on the movement of the particles through the quantum potential, but there is no reciprocal reaction of the particle on the wave which violates the principles of classical mechanics by virtue of his third postulate. However, it should be borne in mind that the theory was elaborated to show that there may be a causal, not necessarily classical, interpretation of quantum phenomena. At present, the de Broglie-Bohm's theory retains a small number of followers in the community of physicists and philosophers, but it is clearly outside the mainstream of physics research.

The next non-local but deterministic theory of quantum processes that has deserved some attention from the community of physicists is that of "*multiple worlds*". This theory originates in a work of Everett in 1957, although the denomination of "*multiple worlds*" arrives later. This work arose in the framework of an investigation for a doctoral thesis that Everett was doing and in which he sought to apply QM to the Universe as a whole. It is clear that this introduces serious conceptual difficulties, among others the derivations of a function or wave vector of the universe, since nothing remains outside this system to interact or intervene in it and produce the reduction of the wave function. So the problems of interpretation become more acute compared to what Everett postulated: the wave function evolves in time only and according to the Schrödinger equation. In other words, Everett eliminated the process of reducing the wave function. Apart from this, he followed the guidelines of the orthodox QM. To see the scope of this concept, we should refer to the problem of measurement in QM. For this we resort to the Dirac abstract notation according to which a wave function is written in the form $|\psi\rangle$. Now, we have already seen that in the measurement of the spin of a particle, let's say of an electron along an arbitrary direction, the only two possible results are "*spin up*" or "*spin down*", that to simplify the writing we will identify them with the symbols "+" and "-" respectively. Now, the postulate of expansion of QM tells us that the wave function of the electron before the measurement is made will be given by the superposition $|\psi\rangle = \alpha|_+\rangle + \beta|^-\rangle$, where the meaning of the coefficients of the expansion is such that $|\alpha|^2$ and $|\beta|^2$ are the probabilities that the measurement yields respectively "*spin up*" or "*spin down*". In this wave function, the two possible states of the electron are present in a linear superposition.

If we now measure the spin of an electron (it is not necessary to stop to consider the details of the measuring device), the measuring instrument will only show one of the two results, "*up*" or "*down*", but since both results are possible with a certain probability, the linearity of the Schrödinger equation tells us that the new state of the system constituted by the electron and the measuring device must be $|\psi\rangle = \alpha|+, \mathrm{up}\rangle + \beta|^-, \mathrm{down}\rangle$. But here we have not yet managed to make a measurement since we still have in the description of the system a linear superposition that includes both possible final states of the measuring device and we do not have a single result that is what would constitute a true measurement. Obviously, for there to be measurement, at some point in the process the reduction of the wave function has to take place to go from a superposition to a single state that in our case would be $|\psi\rangle = |+, up\rangle$ or $|\psi\rangle = |-, down\rangle$. Let us observe that if a conscious observer (as a doctoral student could be?) Is situated at the output of the measuring device, the linearity of the Schrödinger equation would lead us to the new state of the system constituted by the electron, the apparatus of measurement and the conscious observer that would be represented by $|\psi\rangle = \alpha|+, up, I^{+}\rangle + \beta|-, down, I^{-}\rangle$, where I^{+} and I^{-} represent the two possible states of consciousness of the observer that is then aware of the corresponding result, and not mediating the reduction of the wave function, we would still have not achieved a measurement. As we have already mentioned, there is a line of thought that proposes that it is precisely the intervention of a conscious mind in the measurement process that causes the collapse of the wave function.

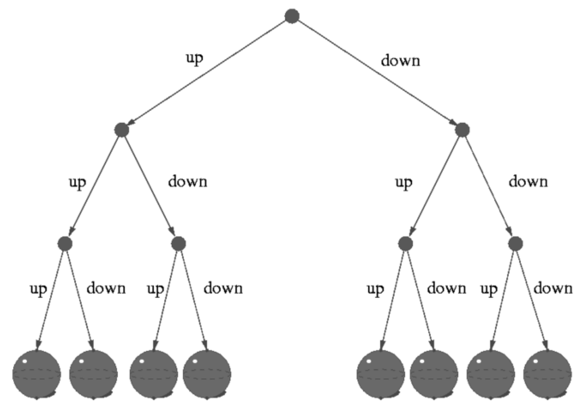

Fig. 2 – Sucessive bifurcations in the spin measurement of an electron.

Returning now to Everett's ideas, our experience teaches us that we never experience the last type of superposition, that is, in which both results coexist in our consciousness. We are aware of one or the other, in this case "*spin up*" or "*spin down*". As we have already seen, the orthodox QM explains this transition between a superposition and a single state with the "*aggregate*" process of the collapse or reduction of the wave function that is produced by the interaction of the microsystem with the macrosystem of the measuring device. The radically different alternative to Everett's proposal is that such a reduction of the wave function never occurs and what happens is that as a consequence of the measurement a bifurcation occurs from which two different worlds coexist, each corresponding to each result of the measurement and in which a causal chain of events develops until a next measurement. That is to say that in a world the observer who measured "*spin up*" would evolve in a totally deterministic way and in another world the observer who measured "*spin down*". In this way reality contains these two worlds with an *"I"* in each one that has had a different experience (the different result of the measurement). Observe that the wave function is still unique, since there is no reduction in it, but it is incorporating components as the measurements follow one another, as shown in figure.

As bold and surprising as it may be, Everett's theory has some attractive aspects. On the one hand, we do not need to worry about what kind of instrument does the measurement, in fact it is not even necessary to have a conscious observer. We do not have the complication of the reduction of the wave function. Inter-subjectivity is assured because two observers who witness the same result in the same measurement necessarily belong to the same world and have no communication with the observers of other worlds. As in this interpretation each branch of each bifurcation is a portion of reality, the world we experience is a tiny portion of the totality of existing reality.

Final reflexion.

We have seen that in the framework of classical physics, there are no great difficulties in accepting the existence of a reality independent of our presence as observers. Nor is there too much difficulty in extending this acceptance of reality to the entities that make up what is called the methodological empirical base, that is, those entities that we can observe in a broad sense, that is with the help of instruments. The problem arises when we want to assign reality to the microscopic entities that belong to the quantum world because their behavior can only be satisfactorily described with the resources of QM, electrons, photons, atoms, elementary particles. We can only assign reality to these entities to the extent that we accept a realistic interpretation of QM, but as this work has tried to show, this is still a highly controversial issue. There is no doubt that much progress has been made in the clarification of many concepts that the orthodox version of the QM, that is to say the interpretation of Copenhagen, left undone. Thus, a theory of decoherence can explain the collapse of the wave function in the context of the same postulates of QM. The problem of non-locality of quantum phenomena also admits a reasonable interpretation if we accept that a system can, under certain conditions, represent a single totality and not be disaggregated into parts. Determinism and causality can be rescued by the non-local theories of hidden variables that we have visited. In short, there are arguments today to defend a realistic philosophy. Of course, it is impossible to demonstrate the existence of a reality external to our conscience, but without doubt that acceptance constitutes a good motivation and makes our effort to understand the world in general much more digestible and justifiable. If there were no reality "*out there*", what would be the point of trying to understand it?

References

1. Klimovsky, G., 1994 *"Las Desventuras del Conocimiento Científico: Una introducción a la epistemología"* A-Z Editora, Buenos Aires.
2. Feynman, R.P., 1965, "*The Character of Physical Law*" Penguin Books, U.K.
3. D'Espagnat, B., 1990, *"Reality and the Physicist: Knowlege, duration and the quantum world*". Cambridge University Press.
4. Maxwell, G., 1998, "*Empiricism and Scientific Realism*", *Philosophy of Science*, Curd. M. & Cover, J.A. Eds., W.W.Norton & Company, London.
5. Maxwell, G., 1998, "*The Ontological Status of Theoretical Entities*", *Philosophy of Science*, Curd. M. & Cover, J.A. Eds., W.W.Norton & Company, London.
6. Von Neumann, J., 1955, "*Mathematical Foundations of Quantum Mechanics*" Princeton University Press, Princeton, N.J.
7. Dirac, P.A.M., 1958, "*The Principles of Quantum Mechanics*", 4th. Ed., Oxford Science Publications, Clarendon Press, Oxford.
8. Greene, B.R., 2005, "*The fabric of the cosmos*" 8ª Ed., Knopf Press, USA,.
9. Gribbin, J., 1994, "*In search of Schrödinger cat*" Bantam Books, USA.
10. Baggot, J. "*The meaning of quantum theory*" Oxford University Press, 1992.