Can we consider Quantum Mechanics to be a Description of Reality ?

Hervé ZWIRN

Centre de Mathématiques et de Leurs Applications
Unité Mixte de Recherche UMR 8536 - CNRS et ENS Cachan
&
Institut d'Histoire et de Philosophie des Sciences et des Techniques
Unité Mixte de Recherche UMR 8590 - CNRS et Université Paris1
herve.zwirn@m4x.org

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Abstract

The paper deals with the status of Quantum Mechanics as a description of reality when quantum formalism is supplemented with the decoherence mechanism. The reasons why it is often argued that Quantum Mechanics provides nothing more than a description of the appearance of reality are examined. Then, through a comparison with Relativistic Mechanics, it is showed that, were the very notion of reality not questionable, it would be possible to support the idea that it provides a description of this reality and not only of its appearance.

1. Classical Physics

In this paper, we examine the different status of Classical Mechanics, Relativistic Mechanics and Quantum Mechanics as description of reality. We will start by Classical Mechanics and the reasons why we accept it.

In the intuitive framework of the layman, the objects we see around us are considered as existing by themselves and independently of any observer. So, the world (including objects, strengths,…) is considered as existing as such. This is what is called reality. It is usual to consider Classical Physics as a good description of this reality. In particular, the description given by Classical Physics is quite close to the appearance of reality and for that reason the interpretation of the classical formalism is not a problem. That means that in a naïve realist attitude framework (the intuitive framework of the layman), the world as it appears through the phenomena (I should perhaps say the world identified with the phenomena) seems to be correctly described by the classical formalism which is never in conflict with our intuitive perceptions contrary to the relativistic formalism or the quantum formalism. For the layman, who never does sophisticated experiments, Classical Physics is in perfect agreement with the real world and it is useless to raise any particular problem of interpretation. The theoretical terms of Classical Physics seem all to have an unproblematic real referent and the classical laws are easily understandable through intuitive processes.

This description is actually much too optimistic. Classical Physics is roughly made up of Newtonian Mechanics, Maxwell Electrodynamics and Boltzman Thermodynamics. Now, these three theories contain theoretical entities and laws that are neither easy to comprehend nor simple to put in correspondence with intuitive phenomena. According to the intuitive layman's description of the world, a body thrown with a non zero initial speed doesn't go on indefinitely, the existence of electromagnetic waves is not immediately obvious and the entropy of a gas is not a concept that seems to be of a direct utility in everyday life. Let's also recall Newton's reluctance to describe gravity as a force acting at a distance even if it was needed by the formalism of his theory.

So, the world description of Classical Physics does not, in the end, conform to its naïve appearance as well as we might think a priori,.

However, we are so used to the description given by Classical Physics that today nobody feels uncomfortable with it. We admit easily that if we never see a body thrown with an initial speed to pursue its course indefinitely as the inertia principle says, it is because of frictional resistance impossible to reduce to zero in the real world contrary to what happens in the idealised world that the theory describes. Similarly, if we can't directly perceive most electromagnetic waves, we know through appropriate devices how to make them appear and nobody would deny that they exist. Their frequent use through radio and television has made them totally familiar things to us. The concept of a force acting at a distance is no more strange and even entropy has become a familiar word.

We have admitted at the end that even if literally speaking the description of the world given by Classical Physics is not strictly in agreement with its appearance, the differences are perfectly understandable: they are due either to an idealisation of the formalism or to our imperfect human means of perception. Then this description is commonly accepted and it is considered as useless to wonder about the interpretation of classical formalism.

2. *Quantum Physics*

The situation is totally different as far as Quantum Mechanics is concerned. Quantum formalism has raised a lot of debates and many different interpretations have been proposed. It is through a comparison between the status of Relativistic Mechanics and Quantum Mechanics that I would like to examine the reasons why many authors (including myself in previous works [1]) hesitate to consider that Quantum Mechanics provides an adequate description of reality (whatever this word could mean and we'll see this is part of the problem).

The hard debates around quantum formalism at the beginning of Quantum Mechanics (specially the famous debate between Einstein and Bohr) are well known. At that time the arguments were essentially focused around the problem of indeterminism. Quantum Mechanics is a probabilistic theory. It provides in general only probability that such and such measured quantity has such and such value. It doesn't know how to predict the result of a future measure with certainty even when the initial state of the system is known perfectly. This default seemed unacceptable to Einstein who thought that a physical theory must give certain results and not probabilistic ones. Of course, Einstein was aware of the fact that even in classical physics it happens sometimes that one cannot predict the result of a future observation. But when that happens the reason why is always that one doesn't know the state of the system with enough accuracy, which is the case if there are too many different components (as for example the molecules of a gas) or if it is not possible to precisely measure the initial state. In Quantum Mechanics, this is totally different. The probabilistic side of predictions is due to the very essence of the systems and their dynamics. This was not acceptable for Einstein who thought that Quantum Mechanics formalism was not complete because it didn't allow to describe the states of the systems with enough details as to be able to do non probabilistic predictions. He was asking for a way to add some other variables in the formalism in order to obtain predictions that are sure. This attempt is called the hidden variables theory approach[1].

It is well known that this debate reached its culminating point with the formulation of the famous Einstein-Podolski-Rosen paradox [3] (more usually known as the EPR paradox) and that the thought experiment stated by EPR was translated into testable inequalities, which state some correlations between measurements done on a pair of particles, by John Bell in 1964 [4]. These inequalities are entailed by the principle of separability which says roughly

[1] For an overview see Belinfante [2].

that two systems which have interacted in the past, have no further direct and immediate influence on each other once they are spatially separated. The point is that the rules of calculation of Quantum Mechanics imply that these inequalities can sometimes be violated. This resulted in a gradual move from the problem of indeterminism to the problem of separability, a property that the macroscopic objects of our current world respect contrary to the microscopic objects described by Quantum Mechanics.

This strange behaviour joined to the fact that quantum formalism forbids in general to consider that the physical properties of systems have definite value before having been measured led many physicists to adopt a reluctant attitude towards considering Quantum Mechanics as a satisfying description of the world even though none of them could deny the validity of the theory as a prediction tool. As I mentioned earlier, many attempts have been made to build alternative theories whose formalism would allow to describe objects as having at anytime well defined properties and such that spatially separated objects could always be independent and such that non probabilistic predictions become possible. This is a very natural attitude: what is looked after is a theory allowing us to get back to the comfortable picture of the world given by classical physics and to abandon these strange properties brought by Quantum Mechanics.

The final answer to the possibility to build such a theory has been given by a series of experiments that culminated in the beginning of the eighties. In 1982, Alain Aspect [5] showed with the greatest accuracy that Bell's inequalities (that provides us with a testable criterion of separability) are actually violated in our world. That means that we have to abandon any hope to build a theory both describing in a correct way the real world and keeping the good old properties of Classical Physics. Every empirically adequate theory will have strange and shocking aspects.

3. Decoherence

Once it has become clear that the strange features of Quantum Mechanics don't come from an imperfection of the formalism but actually from real aspects of observed phenomena, one has to make up one's mind to use it to build a picture of the world, which is not so easy. Beyond the difficulty to get back Classical Physics as limit of Quantum Mechanics when the Planck constant h tends to zero (which is due to the fact that the quantum formalism is not analytic in h), the difficulty to give interpretation of Quantum Mechanics comes mainly from what is known as the measurement problem. In the beginning of the eighties, this problem has been at least partly solved through the decoherence mechanism sometimes called the environment theory. So, I am going to explain briefly what is the measurement problem and its proposed solution.

In the quantum formalism, there are two different ways to compute how a system evolves. The first one, which is to be used when there is no observation on the system, is the Schrödinger's equation. The second one, called the wave packet reduction principle, is used when a measure is done. This could raise no difficulty if the cases in which it is the first or the second way to compute that has to be used were clearly separated. But, it happens that some experiments can lead to different points of view depending on the fact that the measurement apparatus and the observer are considered to be included in the system or not. If they are, the Schrödinger's equation must be used. If they are not, the reduction principle must be used. Both points of view are equally justified. Yet, the predictions made using the Schrödinger's equation are totally different from those made using the reduction principle. In this latter case, the predictions are in agreement with the observed facts (once the probabilistic side of them is acknowledged). However, in the former case, when the measurement apparatus and the observer are considered as included in the system, the prediction is that the apparatus (for example a needle on a dial) should be in a superposed state for which the needle has no definite position. Of course, such a state has never been observed. Moreover, even the observer should be in a superposed state of consciousness! For various reasons this trouble is not eliminated simply by saying that for macroscopic objects such as apparatus, one has to use necessarily the reduction principle. It would be too long here to give the details of the numerous debates around this difficulty or to present the many different solutions that have been proposed to solve it before the decoherence mechanism[2]. I would simply like to emphasize the cumbersome aspect of this problem for any direct attempt to use the quantum formalism as a description of the world. From this formalism, it emerges that it is in general impossible to think that the properties of a physical system own definite values excepted when they have just been measured. In particular, the value of the position or the value of the momentum of a particle is generally not unique. This is obviously an important difficulty since our usual world is not like that. The tables and the chairs always seem to have (and we are tempted to say have and not seem to have) a definite position and a definite speed. How is it possible to reconcile this trivial fact with the apparently opposite predictions made by Quantum Mechanics?

[2] See for example Wheeler and Zurek [6].

One solution is given by the decoherence mechanism, proposed in the eighties by Zurek [7], following Zeh [8], who noted that the environment in which all physical systems are plunged must be taken into account. It is not possible in this paper to present a detailed description of this mechanism but only to sketch a very brief one. As we have seen, the measurement problem comes from the fact that if, as it seems legitimate to do it, we consider that the apparatus is included in the system, then the apparatus is in a superposed state after the measure, i.e. after the interaction with the system on which something is measured. The decoherence mechanism prescribes to deal with a big system including not only the apparatus and the observer but also the environment. After the measurement, this big system is also in a superposed state. That is true for the environment and also for the initial system (on which the measurement is made) and the apparatus. And there is no definite value for the measured property. So what ? The gain comes from the following remark: as a human observer, we can't observe all degrees of freedom of the environment (for example, all the positions and speeds of the molecules of the ambient air). That's impossible for us. Now, to predict what we are going to see about the apparatus (for example to predict the position of the needle) from the big system state, Quantum Mechanics says that we have to use a special operation (called taking the partial trace of the density operator of the big system state) which gives the state of the apparatus from the big system state. Now, it appears (apart from some subtleties that I will leave aside) that the state we obtain through this operation is a state for which the measured property has a definite value (that means that the apparatus needle has a definite position).
So, one could think that the problem is solved and that there is no difficulty left preventing to consider that Quantum Mechanics gives a good description of reality as it appears in our everyday life since it is possible, inside its framework, to get back unique values for all the apparent properties that macroscopic objects have.

4. Is the measurement problem solved ?

This position raises nonetheless some difficulties. The main one is directly linked to the decoherence mechanism and there is still a debate between the position consisting to accept that Quantum Mechanics with the decoherence mechanism provides a correct description of the world and the position pretending that it provides only a description of the appearance of the world[3].

[3] On this subject, among many other references see Zwirn [1], Zwirn [9], d'Espagnat [10] and Soler [11].

It is true that the decoherence mechanism gives at least an explanation for the way phenomena appear. It allows to understand why macroscopic objects never appear in superposed states. But if the decoherence mechanism is analyzed, it becomes clear that the ultimate reason for that is due to the limitation of the human possibilities of measurement. This is because we can't measure all the degrees of freedom of the environment (such a measure will require apparatus larger that the whole universe). If we were able to do it, we would see that in fact, the system, the apparatus and the environment stay in superposed states. The conclusion is that even if these systems are in superposed states, because of our human limits, we can't be aware of the superposition. Even if they are in superposed states, we perceive them as if they were in a state whose properties have defined values. This analysis has led many physicists to adopt a position according to which Quantum Mechanics gives only a description of the classical appearance of the world. It allows to understand why the macroscopic world seems to be classical but it must not be interpreted as explaining how systems become classical after decoherence since they actually stay in quantum superposed states.

I would like to suggest now that perhaps it is possible to adopt a more optimistic view and to explore the way to give to Quantum Mechanics the same status as a description of reality than the one given to Relativity.

When we say that decoherence explains o*nly* the appearance of the world, we implicitly accept the idea that, not only does the world *appear* to be classical but also that it *is* classical. So "the decoherence explains only the appearance of the world" means that even though decoherence explains the appearance of the world, it explains only that, hence it doesn't explain the remaining part, that is the real nature of the world. But if we accept the fact that the world is of a quantum nature, then a theory explaining its appearance and saying that the world, though it appears as if it was classical, retains a quantum nature, is right. Whereas Classical Mechanics which explains also the appearance the world but says that the world is of a classical nature is wrong. In this case, it is fair to say that it is Classical Mechanics that explains only the appearance of the world.

Perhaps at this stage, it is interesting to ask: why is it necessary to explain the classical appearance of the world? This is because Quantum Mechanics describes the world with quantum states and that we associate with quantum states strange effects that we usually don't see. For example, the superposition of positions is something that we never see with the objects around us. This is the reason why we try to explain how, from a quantum description it is possible to reach a classical description more in agreement with what we are used to observe. But, in the case where a description, though quantum by essence, would have no observable effect different from what a classical description would give, it should be possible to accept this description as such. Put differently, if the description of the state of a system through the quantum formalism after decoherence is not classical but has no non classical observable effect, then such a state, even quantum, is acceptable as it is, and there is no need to wonder if we must or not assimilate it to a classical state. I refer to this debate because of the numerous discussions about the question whether it is legitimate or not to consider that a quantum state that has no observable effect different from a classical state can be assimilated to a classical state. The answer given by Bernard d'Espagnat and myself in previous works was a negative one. I think now that this negative answer was coming from our a priori refusal to consider that a quantum state could look like a classical state. But one lesson from decoherence is the possibility of a classical looking quantum state.

Hence, it is possible to present decoherence slightly differently: The reservation on totally accepting decoherence as giving us a correct description was due to the refusal to consider that Quantum Mechanics was giving more than a description of the appearance because according to Quantum Mechanics, the system was remaining in a quantum state. If we seriously believe (and we must do) that a quantum state can sometimes look exactly like a classical state then it is possible to cancel this reservation and to adopt the idea that decoherence is the solution of the measurement problem since it predicts the state of the system after the measure, that this state is a quantum one and nonetheless that it is in perfect agreement with any observation. The fact that this state is a quantum one is not a problem since we can't test directly its strange effects. So we are dealing not only with the appearance of empirical reality but with empirical reality itself. If it was possible for us to do the adequate experiments we would see that this reality is not identical to a classical reality much in the same way that it is possible to detect many different electromagnetic waves through apparatus even though the visible light is the only part of them we can directly see. The fact that these experiments are forever impossible to do is a secondary aspect of the question. So, perhaps the main lesson of decoherence is that some quantum states can look like classical states.

5. Relativistic Physics

To reinforce my argument, I would now like to draw a parallel with the difference between the newtonian world and the relativistic world. For low speeds, we can have the feeling that the world is newtonian. The theory of Relativity predicts that this is not the case, but for usual speeds, it is impossible to see the difference. Strictly speaking, this is not totally true and it is much easier to measure the difference between Newtonian Physics and Relativistic Physics even at low speeds, than it is to measure the entanglement between a system and its environment. But it is only a question of degree and not of nature. It could then be possible to criticize Relativity and to pretend that it provides only a description of the appearance of the world. But nobody does that. Everybody knows that even if the world at low speeds seems to be newtonian, it is actually relativistic and that precise measures could make the differences apparent. Hence it is agreed that relativity provides a genuine description of reality.

The parallel is clear: even if the world appears to be classical (which means only that its appearance is compatible with a classical description) it is actually quantum. What is new is that, thanks to the decoherence theory, a quantum description and a classical description are both compatible with all human possible observations. It is then possible to argue in favour of the idea that Quantum Mechanics with decoherence is a good description of reality and that it is Classical Mechanics that is only a description of the appearance of reality.

So, are we satisfied ? Not really! There are still many difficulties. The first one is that, independently of the measurement problem, the very notion of reality is significantly manhandled by Quantum Mechanics. For example, it is forbidden to think that physical systems have definite properties when no measurement is done. Moreover, the extension of Quantum Mechanics that takes Special Relativity into account, the so called Quantum Field Theory, even says that the existence of a particle is not a well defined property. The number of particles in a state is not a fixed number either. On the top of that, non separability and entanglement between systems forbid us to think that objects are distinct entities. Contrary to the theory of Relativity which is clearly a mechanics of well identified macroscopic objects, Quantum Mechanics is strictly speaking the theory of one object: the universe as a whole. Hence, it is no more possible to keep a simple realist attitude with the idea that the world is made of many well localised objects with well defined properties and interacting through mechanical strengths (what Bernard d'Espagnat called a multitudinist view of the world [12]). That means that, even if some quantum states can look like classical states, it is not possible to think that reality is similar to the picture given by Classical Mechanics. And if the concept of reality becomes fuzzy it becomes less easy to consider that Quantum Mechanics gives a correct description of the real world.

So the hard objection to the acceptance of Quantum Mechanics as a description of reality could come not from the fact that Quantum Mechanics describes only the appearance of the world but from the fact that reality as it is conceived in Classical Mechanics as has no place in Quantum Mechanics. Thus, if the very idea of reality is to be retained, the reality which Quantum Mechanics is a description of is totally different from the one traditional realists rely on.

6. Conclusion

At this stage, the reasoning may seem puzzling. So, let me put it a bit differently. Assume that you have a discussion with a physicist who is a realist and who claims that decoherence is the solution of the measurement problem (for example Zurek, in his first papers [13]). Your first answer is to say "you are wrong: decoherence explains only the appearance of the world and not the real nature of the world". In this answer, you are implicitly assuming that the realist thinks that the appearance of the world and the nature of the world are both classical and also thinks (as many physicists do) that decoherence forces the system to be in a final classical state, what you deny. Now, as we have seen, the realist could actually think that the appearance of the world is classical but that the real nature of the world is quantum. It will be the case if his position stems from the fact that some quantum states can look like classical states. In this case, it seems fair to accept his claim that Quantum Mechanics and decoherence give a good description of the world. But a closer analyse shows that, relying on the fact that some quantum states can look like classical states, what he thinks is that even if the nature of reality is quantum, there is no significant difference with a classical reality. And at this stage, comes the big trouble from the fact that Realism (at least simple forms of Realism) is actually not compatible with Quantum Mechanics. And the reason why you finally disagree is that you can't accept the traditional realist framework.

Your final conclusion is then that Quantum Mechanics can be considered to be a good description of reality if by reality you mean something totally different from what is usually called reality by traditional realists.

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