Quantum Mechanics and Paradigm Shift

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Abstract
It has been argued that the transition from classical to quantum mechanics is an example of a scientific revolution, in which there is a paradigm shift from the classical, simple-minded way of understanding reality, to the quantum, sophisticated new worldview. I will argue in this paper that this is not the case: the quantum world might not be that alien to our common sense, after all.

1. Introduction

Since the first proposal of quantum theory, physicists have wondered what to make of it: they can use the theory for their experiments but they have trouble understanding what it means. It is commonplace to consider quantum mechanics as a mysterious theory at best, especially when confronted with its predecessor classical mechanics, in which everything was clear and well understood. In particular, the world-view that seems to be depicted by quantum theory is so radically different from the one of classical physics that many have identified the transition from classical to quantum mechanics as a prototypical example of a paradigm shift, a scientific revolution as famously described by Thomas Kuhn: while according to classical mechanics the world is made of particles, waves and fields, the quantum world seems to be populated by mysterious objects that can be particles and waves at the same time, and in general by entities that appear to be able to be in more than one places at once. To cut a long story short, it seems that we moved from the paradigm of classical mechanics to the paradigm of quantum mechanics, and during this transition we completely changed the way in which we look at things.

This understanding of quantum theory and of its relation to classical mechanics is so widespread that it is also shared by the layman: literally, almost everyone thinks that quantum mechanics is "crazy", and that after quantum mechanics scientists had to radically change their ways to understand what science does and how they are supposed to practice it.

In this paper I wish to challenge the necessity of this view: I argue that classical mechanics and quantum theories are not necessarily as radically different as they have been depicted so far. In fact whether classical and quantum mechanics are radically different ways of describing nature or not is going to depend on what we understand quantum mechanics to be.

2. Kuhnian Revolutions

Thomas Kuhn is famous for his idea that science evolves through different stages: a first stage of immature science (pre-science), a further stage of normal science (in which a *paradigm* is acquired), and a third stage of revolutionary science (in which happens a paradigm shift).

According to Kuhn, the period of normal science is based on a paradigm: a set of theories, methods, metaphysical and epistemological theses that science, at a certain point in history, accepts. The paradigm dictates what puzzles science will work on, and what counts as an adequate solution to those puzzles, how science should be practised. Paradigms, Kuhn observes, often have anomalies: predictions not fulfilled, inconsistencies and so on. Normal science works with them until there are too many anomalies, and not enough solutions. Different scientists offer different solutions, and the paradigm becomes fractured. There is no longer a unified worldview, and then at some point there is crisis. Therefore there is revolution, which involves sweeping away the whole old paradigm, its theories, methods and standards, and starting from scratch. Revolutionary scientists paint over the canvas, to draw in a new outline, which normal scientists will go on to fill in.

Kuhn believed that the typical example of paradigm shift is the passage from Aristotelian physics to the Copernican view of the universe. Others have claimed that also the shift from classical to quantum mechanics can be view in Khunian terms. Kuhn actually made further claims about the nature of paradigm shits (among other things he claims that theory change is holistic, like a gestalt-switch, and that theory choice is not rational), in addition to the more controversial thesis that theories belonging to different paradigms are incommensurable: they lack a common measure, so they cannot be rationally compared. Be that as it may, one could stick with the weaker thesis that worldviews radically change in the history of science, and with them also change the ways in which physics is used to do metaphysics (if it can be used at all). The transition from classical to quantum mechanics has been taken to be another example of scientific revolution: quantum mechanics is so radical, it is claimed, that the usual classical schemas do not apply any longer.

Let us see in the following sections whether or not it is really the case, first analysing classical theories and then moving to quantum theories.

3. Classical Theories

As we all know, Classical Mechanics is not a very controversial theory: according to this theory the world is made of particles, mathematically represented by points in three—dimensional space, which evolve according to a law, mathematically represented by a second order differential equation, whose solutions provide the possible trajectories of the particles.

The clear metaphysics of the theory ("everything is made of particles") grounds a scheme of explanation that allows determining the properties of macroscopic physical objects in terms of the behavior of the fundamental objects in the theory. In fats, in classical mechanics, any physical body (gases, fluids, and solids) is satisfactorily described as a collection of particles. The story the theory tells us about the macroscopic world is a "geometrical story": a table is just a table-shaped cluster of microscopic particles.

Once the particles and the way in which they evolve are specified, everything else follows: the solidity of a table, the localization of a comet, the transparency of a pair of glasses, the liquidity of the water in this bottle, the compressibility of the air in this room, and so on.

Arguably, in classical mechanics (as well as in classical electrodynamics) we can identify macroscopic properties more or less straightforwardly given how the microscopic particles combine and interact to form complex bodies.

In other words, any property of the macroscopic physical world can be appropriately "read off" from the histories of the particles. Each macroscopic property z will be a (very complicated) function F of the particles x: z=F(x). That is, we have complete reductionism with respect to the primitive ontology of a theory[1]. It seems reasonable that even if we move from an ontology of particles to one of fields, also in three—dimensional filed, things will not fundamentally change in this respect.

Let us see how that is supposed to works through some examples. First, we can explain why a table is solid on the basis of the fact that it is composed of particles that interact electromagnetically such that it is impossible for another object, like for instance my hand, to penetrate them. Next, suppose we wish to account for the fact that a comet has a given localization at a given time. One can accomplish this in terms of the microscopic components of the comet and their interaction with each other: the particles interact to form a solid object whose motion (and therefore its localization at different temporal instants) can be just as effectively described by its center of mass. Also, the transparency of an object such a pair of glasses can be explained in terms of the electromagnetic forces acting between the particles composing the glasses, which are such that incoming light--rays will completely pass through them.

Similarly for fluids: a property like the liquidity of water can be explained in terms of the very weak interaction between the microscopic constituents of water that allow it to change shape with the container. In addition, the behavior of gases is accounted for considering them as composed by non--interacting particles colliding with one another. This is what happens when we derive thermodynamics from statistical mechanics: what in thermodynamics we call pressure, volume, temperature of a gas are derived from the fact that gases are composed of moving particles. Given that air is a gas, and given that a gas is just a collection of non--interacting particles, we can also explain why air is compressible: it is possible to reduce the distance between the particles in it almost as much as we want.

These examples show how in the classical framework we have a clear and straightforward scheme of explanation: given the particles at the microscopic level, one can employ standard methods to determine the properties of familiar macroscopic objects.

4. Quantum Theories

As we just saw, classical mechanics and classical electrodynamics provide two paradigmatic examples of how physics tells us about the world: in the scientific image there are particles and fields that describe matter microscopically, and the manifest image, in which there are macroscopic objects with their properties, is obtained considering the histories of such particles and fields in the appropriate macroscopic limit. It is a very nice explanatory scheme: it is straightforward and clear. In the words of Kuhn, one could say that they provide a paradigm.

Too bad it seems we have to abandon it once we consider quantum mechanics: we need to change our paradigm. In fact several extremely strong assertions have been made about quantum theories: from the claim it is impossible to be realist if quantum mechanics is true, to the idea that the observer can create part of reality, to the insistence that the “old'', classical way of understanding the world we just described is not suitable any longer.

[1] An antireductionist would object to this, but granting that reductionism is possible, this is how it is supposed to work.

The reasons for these attitudes can be perhaps understood by briefly recalling the history of quantum mechanics. At the end of the 19th century, the Newtonian picture of the world was commonly accepted, even if there were several puzzles: there were experiments whose results did not come out as the theory predicted. Some of them suggested the idea of quantization: a discretization of the values certain physical quantities can assume that does not substantially challenge the classical hypothesis that physical objects are made of particles. Other results suggested instead a change in the ontology: some experiments were taken to show that particles sometimes behave like waves. But particles and waves are incompatible ontologies[2]! As Niels Bohr, one of the founders of quantum mechanics, emphasized, it appears that we need to revise our ways of understanding and describing reality: particles and waves are obsolete concepts, inadequate to represent the quantum reality, and should therefore be abandoned. Bohr argued that we lack the proper concepts to describe the quantum world, and that all science can do for us is to predict the results of measurements. In addition, since in the quantum world superpositions are possible, the laws of classical logic such as bivalence do not hold any longer: a particle can be here and and not here at the same time. As a consequence, we need to develop a quantum logic that would account for that.
Trying to save the classical paradigm, Louis de Broglie introduced a particular wave, the wave function, to account for the behavior of particles: he proposed to associate such wave to each particle as a "guide field'' [deBroglie 1928]. The evolution of the wave function was later described by Erwin Schrödinger by his famous equation. De Brogie's ideawas later abandoned (perhaps too quickly) on the basis of some heavy criticism by Wolfgang Pauli at the 1928 Solvay Congress. In addition, some other results (such as Heisenberg's uncertainty principle, and John von Neumann theorem [von Neumann 1932]) were taken to show that quantum theories had to be about the wave function, and not about particles. A further problem, however, was that the attempt to interpret quantum mechanics in a realistic fashion realistically as a theory about the wave function seemed to fail.
In fact, when Schrödinger tried to do so, he discovered the so--called measurement problem: if the wave function completely describes physical systems, and it evolves according to the Schrödinger equation, then "impossible" macroscopic superpositions which we clearly never observe (such as the superposition of an alive and a dead cat) are produced.
Some proposed to solve this problem introducing the observer actively into the theory: the observer's conscious observations "collapse" the wave function to one of the terms of the superposition [Wigner 1967], [von Neumann 1932].
There are many reasons to consider this approach unsatisfactory (first of all because of the unfortunate reference to the observer in the formalization of the theory [Bell 1987], [Goldstein 1998]), but the common understanding was that the situation left no other escape: the previous way of understanding things in terms of stuff in space moving in time was not applicable any longer, so no matter how much one dislikes the alternatives, they are what we are stuck with.

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[2] Particles have definite positions in time, and their temporal evolution is represented by a trajectory in space--time; in contrast waves are delocalized, spread--out objects that can diffract and interfere with one another.

If this is the case, then either the wave function is collapsed in one of the terms of the superpositions by an observer; or there are two distinct and fundamentally irreducible worlds, the classical and the quantum one. Neither of these two approaches is close to the previously accepted paradigm of classical mechanics in which the world was made of microscopic particles that compose macroscopic objects. Here, then, we have a paradigm shift: roughly put, in one worldview consciousness actively participates to physics, in the other the laws of classical logic are not valid any longer.

5. Quantum Theories without Observers

Luckily, these theories did not remain the only one on the market for long. Eventually, in the 1950s new and less problematic proposals to solve the measurement problems were made. Einstein did not like the status of quantum mechanics and proposed an argument to show that the current formulation of quantum theory was incomplete and should be supplemented by "hidden variables" [Einstein Podolsky and Rosen 1935].

David Bohm [Bohm 1952], perhaps with this idea in mind, revised and updated de Brogie's particle--wave theory and showed that his theory solves the measurement problem. In Bohm's theory the description of any physical system is provided by the wave function supplemented by "hidden variables", the particles' positions. In this way, the symmetry among the various terms of the superpositions (dead and alive cat) is broken by the presence of the particle trajectories, and the measurement problem is resolved: the cat is dead if the trajectories of the particles composing the cat fall in the support of the dead-cat wave function; she is alive if they fall in the support of the alive-cat wave function.

However, this theory had an unfortunate fate, since von Neumann's theorem was already taken to prove that hidden variables are impossible. This conviction was reinforced by certain presentations of Bell's inequality [Bell 1964]. As a result, Bohm's theory was dismissed for a very long time: people believed that there was something wrong with it, even if it was not clear what. Only fairly recently it was appreciated that the interpretations of these results were mistaken: it is possible for the quantum world to be made of particles, and there is nothing wrong with Bohm's theory[3]. Still, only few scholars took the theory seriously, and some of them developed a better formulation of it that now goes under the name of Bohmian mechanics[4].

Even if there are particles in Bohmian mechanics, people still insisted on the wave function. In fact, the other solutions to the measurement problem focused either on accepting the macroscopic superpositions, or on eliminating them. Hugh Everett [Everett 1957] developed the so called many-worlds interpretation, in which the terms of the superpositions are interpreted as belonging to different worlds to which we have no access, so that everything that can happen (all superpositions) will happen, but in a different world[5].

Another possible response to the measurement problem is the GRW theory, proposed by

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[3] For a correct presentation of Bell's theorem see directly [Bell 1964] or [Dürr et al. 2004], where also the so--called "no-go" theorems against hidden variables theories are discussed.

[4] See, for example, [Dürr et al. 1992], [Goldstein 1996], and [Allori and Zanghí 2004] for a review of Bohmian mechanics.

[5] See among others [Barrett 2008], [Vaidman 2002], [Wallace 2002].

[Ghirardi Rimini and Weber 1986]: here the wave function randomly collapses in one of the terms of the superpositions not because of an observer but as a result of a physical law: the wave function in this theory evolves according to a stochastic equation that allows for random spontaneous collapses[6].

The three examples presented above show how it is possible to provide realist interpretations of the quantum formalism that do not rely on the notion of the observer. For this reason they have been called "quantum theories without observers" [Popper 1967], [Goldstein 1998].

6. Wave Function Ontology and the Change in Paradigm

All these theories were naturally taken to be theories about the wave function[7]. That is, the wave function mathematically represents a real, physical field that constitutes physical objects. For this reason such a view has been called "wave function ontology."

One of the strongest arguments for such a view is an argument by analogy. If in a physical theory there is a fundamental equation for the evolution of a given mathematical object, generally we feel justified to take this object to represent physical objects. Consider classical mechanics: the fundamental equation of this theory is Newton's equation that describes the temporal evolution of a mathematical object which is a point in three--dimensional space. It is natural to interpret such object as describing a point--like particle, and this is exactly the way we take it: we conclude that classical mechanics is a theory that describes the behavior of point--like particles. By analogy, we should do the same in quantum mechanics: given that in this theory there is a fundamental equation, Schrödinger's equation, for the temporal evolution of the wave function, we are entitled to take the wave function to represent physical objects as well.

As a consequence of this view, physical space is not the traditional three--dimensional space. Rather, it is the space on which the wave function is defined (its domain): this space is called "configuration space." Historically, configuration space has been introduced in classical mechanics for mathematical purposes. It is constructed from three--dimensional physical space: if there are N point-like particles, each with position r_i in three--dimensional space R^3, then configuration space is defined as the space of the configurations of all particles. That is, an element q of configuration space is given by $q=(r_1,r_2,...,r_N)$. As a consequence, if there are N particles in the universe, configuration space has dimension M=3N. Observe that if one maintains that physical bodies are represented by the wave function, then literally there are no particles, and therefore there is no real reason to call such space "configuration space." The proponents of this view realize that, but the name stick nonetheless.

Since the proposal is to take the wave function to represent physical objects, it seems natural to take configuration space as the true physical space. But clearly, we do not seem to live in configuration space: rather, it seems obvious to us that we live in three--dimensions. Therefore, a proponent of such a view has to provide an account of why it seems as if we live in a three--dimensional space even though we do not. Connected to that problem, we should explain how to "recover the appearances" of macroscopic objects in terms of the wave

[6] See among others[Bassi and Ghirardi 2003] and [Ghirardi 2007].

[7] See [Albert 1992], [Albert 1996], [Lewis 2006], [Wallace 2003] and references therein.

function. This is something that the proponents of such view are working on.
If this reading of the formalism of quantum theories is correct, then even if there is no observers, and the laws of classical logic are still valid, we nonetheless have a paradigm shift: we move from the classical, common-sensical view that there are microscopic objects (particles, and fields) that compose macroscopic familiar objects, to the quantum view in which we all live together in configuration space, and we cannot use any longer the rules of compositionality and reduction as we did in the classical paradigm.

7. Quantum Theories with no Paradigm Shift

The concern with these theories is therefore that, since the wave function lives on configuration space and not three--dimensional space, the explanatory scheme developed in classical theories in terms of a microscopic ontology should be drastically revised: a new explanatory scheme is needed, and nobody has found one yet. Whether or not it is possible to consider the wave function as such have been challenged elsewhere[8], and has little relevance here, since the point is that it is not necessary.
In fact the good news is that we do not have to interpret quantum theories as theories of the wave function. And since the paradigm shift arises from taking the wave function as a describing physical objects, if we do not do that then we might avoid the change in paradigm altogether.
Various proposals have been made of quantum theories in which, as in classical theories, there is *stuff* in space--time, and we can develop a clear explanatory scheme, on the line of the classical one, to account for the macroscopic world. As a consequence, there is no quantum revolution (or at least, not the one advertised so far): the quantum world is less crazy and paradoxical than one would have though. This could be perhaps a disappointment for some, but certainly to others it is a great relief: we still can understand things the way we did before! In this section I am going to describe how this can and actually has been done.
Let us go back to Bohmian mechanics: as we saw, one could think of it as a theory about both particles and the wave function. After all, it is argued, in Bohmian Mechanics we have two fundamental equations, one for the wave function and one for the particles, and they describe what there is. But if we look closely to the structure of the theory we will see that this approach is contrived. In fact Bohmian mechanics is naturally a theory of particles, whose temporal evolution is governed by a Schrödinger evolving wave function. In other words, the wave function in the theory has a particular role: it does not describe matter (points in three—dimensional space do), it describes the way in which matter moves. In this way, it seems more appropriate to think of it as representing a law for the physical objects [Teufel and Goldstein 2001] or perhaps a property of physical objects [Monton 2002], rather than physical objects themselves. With this understanding of the role of the wave function in Bohmian mechanics, then one can start to look to the other quantum theories without observers differently.
The GRW theory, in which the Schrödinger evolution of the wave function is interrupted by random collapses, we seem we just have the wave function. But two distinct GRW-type of theories have been proposed, originally by [Ghirardi Benatti Grassi 1995] and [Bell 1987]

[8] See [Allori Goldstein Tumulka and Zanghí 2010], [Monton 2002], [Monton 2006].

respectively[9]: GRWm, a theory in which matter is described by a field in three--dimensional space defined in terms of the wave function, representing the matter density of physical systems, and GRWf, a theory according to which matter exists in space—time called "flashes", whose rate depends on the wave function[10].

In both GRWm and GRWf the evolution of matter is determined by the wave function, which in turns evolves according to the modified GRW dynamics. In addition, [Allori et al. 2010] have proposed and developed a many--world theory that they called Sm: a mass density field ontology in three--dimensional space, as in GRWm, combined with a Schrödinger evolving wave function which determines the temporal evolution of the primitive variables. A non-exhaustive list of other possible quantum primitive ontologies and their evolutions can be found in [Allori et al. 2008].

In this framework, quantum theories have the same structure as classical theories: there is microscopic stuff in ordinary physical space that moves in time, and this microscopic stuff combine together to form the familiar macroscopic objects of our experience. Because of this, also in these theories we should be able to recover, at least in principle, all the macroscopic properties of physical objects using an explanatory scheme derived along the lines of the classical one.

Indeed, this has been done in the framework of Bohm's theory in [Dürr at al. 2004], [Allori et al. 2002], and [Allori et al 2008b]. In the GRW and many--worlds frameworks, more work needs to be done. In any case, see [Bassi and Ghirardi 2003] and [Goldstein et al. 2011] for some related comments on the matter. An antireductionist, again, would object to this, but the point here is that in quantum theories so interpreted are not worse off than in classical mechanics. That is, whatever can be raised against reductionism in classical mechanics, in principle could also be raised here. But there is no additional problem for reductionism due to just the fact that we are in the quantum framework.

8. Conclusion

The bottom line is this: no paradigm shift is needed to account for the quantum world. If we like to drastically change our way of understanding the world through physics we can, but we do not have to.

First, we do not have to cease to be realist, introduce consciousness into physics, or change the rules of classical logic if quantum mechanics is correct: there are at least three quantum theories (Bohmian mechanics, GRW and many-worlds) that account for all physical phenomena without doing anything of the sort. Second, it has been claimed by the majority that even if we take these theory seriously still we need to revise our way of understanding the world and physics itself. This is not correct: this is not unavoidable. In fact while it is true that our worldview changes if we take the wave function to be a real matter field, we do not have to do so: there are other ways of interpreting the mathematical formalism of such theories in such a way that we can keep our classical paradigm, or at least, a paradigm not so

[9] Here "GRW-type of theories" refers to the fact that in both these theories the wave function evolves according to a stochastically modified Schrödinger evolution.

[10] For more on these theories, see for example [Allori Goldstein Tumulka Zanchi 2008],, [Tumulka 2006].

radically different from it.

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