3-5-2015

Quantum Mechanics and Paradigm Shifts

Valia Allori

Original Citation

"Quantum Mechanics and Paradigm Shifts." Topoi 32 (2): 313-323 (2015).

Quantum Mechanics and Paradigm Shifts

Abstract

It has been argued that the transition from classical to quantum mechanics is an example of a Kuhnian scientific revolution, in which there is a shift from the simple, intuitive, straightforward classical paradigm, to the quantum, convoluted, counterintuitive, amazing new quantum paradigm. In this paper, after having clarified what these quantum paradigms are supposed to be, I analyze whether they constitute a radical departure from the classical paradigm. Contrary to what is commonly maintained, I argue that, in addition to radical quantum paradigms, there are also legitimate ways of understanding the quantum world that do not require any substantial change to the classical paradigm.

Keywords: quantum mechanics; classical mechanics; Kuhnian scientific revolutions, paradigm shifts.

1. Introduction

Since it was first proposed, physicists have wondered what to make of quantum mechanics: 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 particular, in the quantum world there are supposed to be particles behaving like waves and waves behaving like particles, with observers creating reality and consciousness playing a crucial role in physics. Regardless the details, everyone seems to agree that the world-view depicted by quantum theory is radically different from the one emerging from classical physics. Because of this, many have identified the transition from classical to quantum mechanics as a prototypical example of a paradigm shift, so that the rise of quantum mechanics amounted to a scientific revolution, as famously described by Thomas Kuhn. To cut a long story short, the claim is that we have moved from the paradigm of classical mechanics to the one of quantum mechanics, and during this transition, we have to change completely the way in which we look at things through fundamental physical theories. 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 the quantum world is believed to be populated by mysterious objects which we cannot truly comprehend with our obsolete classical concepts. In addition, this paradigm shift is advertised as necessary: there is no possible way of classically understanding the quantum phenomena. For instance, here is how Brain Greene puts it: "But of all the discoveries in physics during the last hundreds years, quantum mechanics is far and away the most startling, since it undermines the whole conceptual scheme of classical physics" [Greene 2005].

In this paper I wish to clarify the situation and answer the following questions: what is a quantum paradigm? How does it differ from the classical one? Does the theory change from classical to quantum mechanics really require a paradigm shift? In section 2 I briefly remind the main claims made by Kuhn regarding paradigm shifts and scientific revolutions, I clarify which parts of Kuhn's views are relevant for the present discussion, and I define the theses I am going to address in the paper. In sections 3 I present the classical paradigm: the main ingredients of classical mechanics, and the way in which it accounts for microscopic and macroscopic phenomena. In section 4 I review the history of quantum theory to show that there is no single quantum paradigm: already in the early years of quantum mechanics there were multiple paradigms, which I dubbed the "early quantum paradigms." They were the ones that historically prevailed and became the orthodoxy. As I describe in section 5, since the `50s a "new quantum paradigm" slowly started to gain popularity. As we will see, even if in different ways, both the early and the new quantum paradigms require radical changes to the classical paradigm. If they all require substantial changes, then the fact that there are multiple quantum paradigms does not undermine the thesis that a paradigm shift in the classical to quantum theory change is necessary. In section 6 I argue instead that, surprisingly enough, it is not the case: there are other quantum paradigms (at least as satisfactory as the one in section 5) which do not necessitate we fundamentally abandon the classical paradigm to account for the quantum world. In section 7 I summarize my conclusions: 1) even if people usually talk about one quantum paradigm, there is actually no single quantum paradigm; 2) both the early and the new quantum paradigms require a substantial paradigm change, even if the former require a change in the fundamental concepts while the latter do not; 3) in contrast with what is commonly believed, having a paradigm shift is not necessary: there are some quantum theories that fit nicely within the classical paradigm, and whether or not there is a paradigm shift is going to depend on what quantum theory one decides to adopt.

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 there is a paradigm shift) [Kuhn 1962] . According to Kuhn, the period of normal science is based on a given paradigm: a set of theories, methods, metaphysical and epistemological theses that scientists, at a certain point in history, accept. The paradigm specifies the ontology of the world, it dictates what puzzles science will work on, and what counts as an adequate solution to those puzzles, it establishes how science should be practiced, and what the aim of science is. Paradigms, Kuhn observed, often have anomalies: predictions not fulfilled, inconsistencies and so on. Normal scientists substantially ignore these problems since they believe them to be ultimately solvable within the framework of the theory, even if they currently have not. At a certain point, though, there are too many anomalies, and different scientists offer different kinds of solution, so that the paradigm becomes fractured. There is no longer a unified world-view, and at some point there is crisis. This leads to a scientific 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 new normal scientists will go on to fill in within the new paradigm.

Note that Kuhn made further claims about the nature of paradigm shits. Among other things, he maintained that theory change is holistic, like a gestalt-switch, and that theory choice is not rational. Moreover, he entertained the even more controversial thesis that theories belonging to different paradigms are incommensurable - they lack a common measure, so they cannot be truly compared. In this paper I do not want to comment on incommensurability or on the rationality of theory choice: I will ignore these aspects of Kuhn's thesis. In addition, since his definition of paradigm is complex and not well understood, I am going to consider that a <u>*paradigm*</u> consists of the following:

1) a world-view: a claim about what exists in the world;
2) a set of methodologies with which a scientist can account for the behavior of macroscopic objects and their properties in connection with the world-view;

3) a set of concepts to define 1 and carry out 2.

Here is what is meant by paradigm shift in this paper:

(PS) paradigm shift thesis: moving from one physical theory to the next our paradigm *radically* changes.

Note that the notion of "radical change" is vague but in an unproblematic way, since it is simply supposed to capture the idea that the change is substantial in some important respect: the world-view, the methodologies, the concepts, or a combination of them. In this way we can define degrees of radicalism to allow for rough comparisons among paradigms: when compared to the a given paradigm p_1, a second paradigm p_2 that requires a change in all three ingredients of the paradigm will involve a more radical change than the one required by a third paradigm p_3 that changes only one of them. Clearly this alone does not allow for a comparison between two paradigms that require a different change in an equal number of ingredients, but as we will see the current specification will be sufficient for our purposes.

Kuhn believed that the typical example of paradigm shift was the passage from the Ptolemaic to the Copernican view of the universe: the change from a world-view in which the Earth is at the center of the Universe, to one in which the Earth is just another planet. He also took the theory change from classical to quantum mechanics as another example of paradigm shift. This view, which is just *PS* applied to the transition from classical to quantum mechanics, is shared also by the vast majority of physicists and even by the layman. It reads as follows:

(PS_cq) paradigm shift thesis (in the classical to quantum theory change): the quantum paradigm is *radically* different from the classical paradigm.

It turns out that many physicists take this thesis a step further. Take for instance what Lev Landau and Evgeny Lifshitz wrote in their milestone book on quantum mechanics: "it is clear that [the results of the new experiments] can in no way be reconciled with the [classical] idea that electrons move in paths. In quantum mechanics there is no such concept as the path of a particle" [Landau and Lifshitz 1958]. In addition to *PS_cq*, they seem to endorse the assumption that not only quantum mechanics is so radical that the classical paradigm has been *contingently rejected, but also it necessarily had to be rejected*. That is, they seem to hold the following thesis:

(NPS_cq) Necessary paradigm shift thesis (in the classical to quantum theory change): 1) the quantum paradigm is *radically* different from the classical paradigm; 2) the quantum paradigm is *necessarily* radically different from the classical paradigm.

3. The Classical Paradigm

The common wisdom is that classical mechanics is hardly a controversial theory, at least in the following respects: according to this theory the world is made of point-like particles in three-dimensional space, which evolve according to Newton’s law of motion, a second order differential equation, whose solutions provide the possible trajectories of the particles through space in time. The clear metaphysics of the theory (“everything is made of particles”) grounds a scheme of explanation that arguably allows identifying macroscopic physical objects and their properties in terms of the behavior of the fundamental objects in the theory. Arguably, in fact, in classical mechanics any physical body (gases, fluids, and solids) can be satisfactorily described as a suitable collection of particles. That is, some sort of *compositionality principle* holds: every macroscopic object is composed of microscopic constituents, the particles. In this way a table is just a table-shaped cluster of microscopic particles. Once the particles and the way in which they evolve are specified, every physical property of such macroscopic objects 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. In other words, we have some sort of *reductionism* with respect to the particles, the fundamental constituents of matter: in classical mechanics we can identify macroscopic properties more or less straightforwardly given how the microscopic particles combine and interact to form complex bodies. Note that an antireductionist would object to this, but granting that reductionism is possible, this is how it is supposed to work. Moreover, the situation does not change much when we consider classical electrodynamics, in which there are charged particles and electromagnetic fields. Contrarily to particles, which are localized entities in three-dimensional space that evolve through time according to Newton’s equation, electromagnetic fields are spread-out objects in three-dimensional space which evolve in time according to Maxwell’s equation. Even if they have their differences, both are mathematically described by objects in three-dimensional space, so that some sort of principle of compositionality and reductionism can still hold.

The bottom line is that in the classical framework we have a clear and straightforward scheme of explanation of macroscopic phenomena: given the particles at the microscopic level (the world-view), assuming compositionality and reductionism (the methodology), one can employ what now are standard methods to account for the properties of familiar macroscopic objects in terms of their microscopic constituents.

4. The Early Quantum Paradigms

Using Wilfrid Sellars terminology [Sellars 1962], in the scientific image of classical mechanics there are particles and fields that describe matter microscopically, and the manifest image, in which there are macroscopic objects with their properties, is obtained assuming compositionality and reductionism. The classical paradigm provides a very nice explanatory scheme: it is straightforward and clear. It turns out, though, that it seems we *have* to abandon it once we consider the quantum world: in order to account for the new experimental data, we *need* to change our paradigm.

The change in paradigm seems to be particularly extreme, for several extremely strong assertions have been made about quantum theories: from the claim that it is impossible to be realist if quantum mechanics is true, to the idea that the observer can create reality, to the insistence that the "old," classical way of understanding the world we just described is not suitable any longer. For instance, here is what reportedly Niels Bohr said to Werner Heisenberg: "Anyone who is not shocked by quantum theory has not understood it" [Heisenberg 1971]. But what exactly is the quantum paradigm? Is there more than one? Do they all involve some radical change to the classical paradigm? Let us briefly recall the history of the development of quantum mechanics to find some insight.

At the end of the 19th century, the Newtonian picture of the world was commonly accepted, even if there were several puzzles: there were theoretical predictions that did not square out with experiments, and there were experiments whose results did not come out as the theory predicted. Some of them, from the stability of the atom, which is impossible to explain with the classical theory, to the Stern-Gerlach experiment, suggested the idea of quantization: a discretization of the values that certain physical quantities can assume. For instance, if energy in the classical framework could be described by any positive real numbers, in the quantum domain it is constrained to assume certain discrete values. This quantization assumption does not substantially challenge the classical hypothesis that physical objects are made of particles, and therefore hardly constitutes a change in world-view: the only difference is that in this new description the "properties" of particles (energy, momentum and the like) are discrete rather than continuous in values, while compositionality and reductionism still can apply.

In contrast, other results suggested a change in the ontology was necessary. For instance, some experiments were taken to show that the concepts of particles and waves are inadequate to describe the quantum world. In fact, experiments like the two-slit experiment shows that electrons, taken to be particles, seem to be able to diffract and interfere like waves. This is problematical since particles and waves are incompatible ontologies: particles, by definition, have definite spatial positions, while waves are defined as delocalized, spread-out objects. Also, waves' trajectories "bend" around obstacles: that is, they diffract. In addition, waves are characterized by their intensity, connected to their energy, and intensities can sum and subtract giving rise to interference phenomena. These behaviors are not allowed to particles, so how can one make sense of the two-slit experiment? Niels Bohr suggested 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. We should talk about *wave-particle duality* instead: electrons, say, are not particles, but dual objects that in certain experiments show their particle side, and in others their wave side. More precisely, Bohr argued that we lack the proper concepts to describe such quantum objects, and that all science can do for us is to predict the results of measurements [Bohr 1949]. Such measurement results are derived in terms of a mathematical object that evolves in time according to an equation typical of a wave, and therefore has been interpreted as a wave, called "the wave function." The equation that governs its temporal evolution is the famous Schrödinger equation.

Does this constitute a shift in paradigm? It seems so: we have new world-view according to which the quantum world is made of classically incomprehensible objects, and they do not compose the macroscopic objects in the classical way. To be more precise, in Bohr's proposal the classical macroscopic world is postulated to exist in addition to the mysterious quantum world. That is, macroscopic objects obey the law of classical physics, which needs to be postulated in addition to quantum physics that governs the behavior of quantum objects.

Many physicists embraced Bohr's paradigm, presumably because they believed that there was not much of a choice. Others instead were not so enthusiast, since this theory is not easy to swallow: even if one passes over the idea of giving up to classical concepts, there is an intrinsic vagueness in the way in which it is defined. In fact, the theory establishes that macroscopic objects obey classical mechanics, but it does not specify what counts as a macroscopic object. In other words, where is the boundary between the quantum and the classical world? To make things worse, this proposal just amounts to give up the possibility of accounting for the whole world (macro and micro) with a unique physical theory, and this is extremely unappealing. Because of these reasons, a good portion of physicists ended up with some sort of anti-realist position because they took Bohr's proposal as a *reductio* for scientific realism in the quantum framework. They endorsed the so-called “shut up and calculate” attitude: if reality is so weird, let's forget about it, and let us stick with what we do best, namely compute the theoretical outcomes of experiments and check whether they come out correctly.

Another group of physicists instead was not so eager to accept antirealism or Bohr’s view without a fight. Louis de Broglie thought of using the wave function to account for the perplexing behavior of the so-thought particles in the two-slit experiment [de Broglie 1927]. He proposed to associate such wave to each particle as a “guiding field:” each particle is “carried along” the wave, just like a small ship is carried along the current of the ocean. This is the reason his proposal is often called “the pilot-wave theory.” In this way, in situations like the two-slit experiment, particles *seem* to behave like waves not because they are neither particles nor waves, but because there are *both* (regular) particles *and* (regular) waves that interact so to produce the experimental outcome. As promising as it sounded, de Brogie's idea was soon abandoned (presumably too quickly, as we will see later) on the basis of some criticism by Wolfgang Pauli at the 1927 Solvay Congress where de Broglie presented his theory: he complained that de Broglie's theory was unable to provide a consistent account of a system composed by multiple particles [Pauli 1927].

To complicate things further, some other results, like the Heisenberg uncertainty principle [Heisenberg 1927], were taken to show that, if quantum mechanics can still be taken realistically as describing an objective quantum world, it *had* to be about the wave function, and not about particles. In fact the uncertainty principle, which literally says that we cannot ever know simultaneously the position and velocity of a particle with absolute certainty, has been taken to signify (quite radically) that if there are particles then they do not possess definite properties, such as positions and velocity; they only acquire one of them after an experiment is made. This seemed absurd, and so people concluded that there are no particles, no points in three-dimensional space that follow in time a given path. If there cannot be particles, physicists with a realist inclination concluded that, if anything, they had to look at the wave function for a candidate to represents physical reality.

Unfortunately, the attempt to interpret quantum mechanics realistically as a theory about the wave function seemed to fail as well! In fact, when Erwin Schrödinger tried to do so, he discovered the so-called “measurement problem” [Schrödinger 1935]: if the wave function completely describes physical systems, and it evolves according to the Schrödinger equation, then macroscopic superpositions, such as the superposition of a cat that is both dead and not dead at the same time, are produced. This shows that there is something wrong in the analysis: we never observe macroscopic objects having contradictory properties. But which assumption is to blame?

These macroscopic superpositions are bad. Note that Bohr did not have them because in his view the macroscopic world is classical and the quantum superpositions are just on the microscopic level, which we already know to be counterintuitive. Some of those who, against Bohr, tried to apply quantum mechanics to everything, and to interpret it realistically, proposed to get rid of the macroscopic superpositions by appealing to the notion of "observer." Roughly put, the reason why macroscopic superpositions are never observed is that the observer plays an active role in the theory: it is her act of observing that "collapses" the wave function into one of the terms of the superposition. But what exactly does that mean? Eugene Wigner proposed that it is the consciousness of the observer that produces the collapse [Wigner 1967]. In this way, a non-physical entity like consciousness determines what physical entities do. John von Neumann instead proposed that Schrödinger's equation does not universally apply. When a measurement is performed, a new law of temporal evolution of the wave function supersedes the Schrödinger equation. This new law causes a random collapse of the wave function into one of the terms of the superposition [von Neumann 1932]. In this way a microscopic quantum object is determined to evolve either deterministically (according to Schrödinger's equation) or randomly (governed by the collapse postulate) depending on a macroscopic phenomenon like the performance of a measurement. Interestingly enough, neither Wigner nor von Neumann commit themselves to say what constitutes the quantum world. Therefore it is unclear whether or not we can think of their paradigm as a realist attempt to make sense of quantum mechanics. Be that as it may, we can turn their approach into a realist one as follows: assume the entities populating the quantum world are the ones described by Bohr; the classical world emerges from the quantum world because either consciousness or the act of observation kicks in. Neither of these two approaches is close to the previously accepted paradigm of classical mechanics: while classically the world is made of microscopic particles that compose macroscopic objects and determine their properties, here we have almost the opposite. In fact in the approaches of Wigner and von Neumann, even if some sort of compositionality is assumed to hold, reduction seems to fail. In other words, even if we assume that in these approaches macroscopic objects are composed of microscopic quantum *stuff*, macroscopic properties are determined not in terms of the microscopic entities but rather either by a macroscopic entity (the act of measurement, in von Neumann's picture), or by a non-physical entity (the observer's consciousness in the case of Wigner's approach).

There are many reasons to consider this kind of approach as unsatisfactory: the unfortunate reference to the observer or the process of measurement in the fundamental formalization of the theory makes it hopelessly vague; the appeal to consciousness is equivalent to the rejection of the completeness of physics. Nevertheless, the common understanding was that the situation did not leave many escapes: the classical paradigm in terms of *stuff* in three-dimensional space moving in time was not applicable any longer. So, no matter how much one dislikes them, they were believed to be, together with Bohr's proposal, the only options. They constitute what we can dub *the early quantum paradigms*.

To summarize: there is no single quantum paradigm, there are many of them. All of these paradigms are radically different from the classical one, so that *PS_cq* seems to be true. In fact, all three elements in the paradigm, the world-view, the methodology and the concepts used, change substantially. In addition, the historical discussion seems to suggest that the necessity thesis *NPS_cq* is quite plausible: as we saw, it was taken to be impossible to use the classical concepts in the quantum domain.

In the next section, I present another kind of quantum paradigm. This will not undermine *PS_cq* since it will still require a radical departure from the classical world-view. But the change will be less substantial in a certain respect: even if the world-view and the methodologies will be radically different from the classical paradigm, the new quantum paradigm presented in section 5 will not need a new set of concepts. In this way, the necessity thesis will arguably start to lose plausibility. Be that as it may, it will be only in section 6 that we will see counterexamples to *NPS_cq*: explicit examples of satisfactory quantum paradigms in which concepts, world-views and methodologies will all be closer to the classical paradigm than we thought possible.

5. The New Quantum Paradigm

The early quantum paradigms did not remain the only ones on the market for long. Eventually in the 1950s less problematical solutions of the measurement problem were proposed. Let us see where they come from starting from Albert Einstein. He notoriously disliked quantum mechanics and proposed an argument to show that its current formulation was incomplete and should be supplemented by "hidden variables" [Einstein Podolsky and Rosen 1935]. Later, though, John Bell proved that one of the assumptions in Einstein's argument had to be refuted in the light of some new experiments [Bell 1964], [Aspect *et al.* 1981]. This assumption is locality: roughly the idea that what happens in a give region of space does not affect what happens in another distant region.

Even if Einstein's proof failed, the idea that quantum mechanics might be incomplete remained in the air. For example David Bohm, presumably with this idea in mind, revised and updated de Brogie's particle-wave theory to respond to Pauli's objection, and showed that his theory also solves the measurement problem [Bohm 1952]. In Bohm's theory the description of any physical system is provided by the wave function supplemented by "hidden variables," the particles' positions. As in text-book quantum mechanics, the wave function evolves according to Schrödinger's equation, while the particles evolve according to the so-called "guidance equation." 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 solved: 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, arguably because a theorem proved by von Neumann, the first of a series of so-called "no go theorems," was taken to prove that hidden variables are impossible [von Neumann 1932]. This conviction was reinforced by a certain (mis)understanding of Bell's inequality and Aspect's results, which were also taken to show the impossibility of deterministic completions of quantum theory. 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 finally appreciated that such interpretation of Bell's inequality and the no-go theorems is mistaken: as we have already seen, Bell's proof together with Aspect's results shows that reality is nonlocal, and the no-go theorems are based on unrealistic and restricted assumptions (for more on this, see e.g. [Bell 1964], [Cushing 1994]). Therefore, there is nothing fundamentally mistaken about deterministic completions of quantum mechanics, like Bohm's theory. Still, only few scholars took Bohm's theory seriously, and some of them developed a better formulation of it that now goes under the name of Bohmian mechanics (see [Goldstein 2001] for a review).

If this is correct, then it is still possible for the quantum world to be described as made of particles following trajectories in three-dimensional space. Nonetheless, even if a particle ontology was now viable, people still insisted on the wave function as the ontology of the quantum world. Presumably, this was due to the fact that in addition to Bohm's theory there are other solutions of the measurement problem, and they all involve the wave function in a fundamental way. Indeed, they all seem to be focused either on eliminating the macroscopic superpositions of the wave function, or on somehow accepting them. Bell's famous summary on how to solve the measurement problem “either the wave function, as given by the Schrödinger equation, is *not everything* or it is not right” [Bell 1987] confirms this attitude: Bohm's theory aims to eliminate superpositions denying the completeness of the description provided by the wave function, and the other solutions, as we will see, will either deny that the temporal evolution of the wave function is given by Schrödinger's equation (so eliminating the superpositions), or they will embrace superpositions entirely. This emphasis on superpositions is clearly suggestive that it is the wave function that was considered as representing matter when talking about the quantum world. Before continuing with this, let me clarify that the solutions of the measurement problem often are called “interpretations of quantum mechanics,” suggesting that they provide an interpretation of the mathematical formalism used in the theory. As the case of Bohm's theory already has shown, they are much more than that: they are *quantum theories*, which provide *different world-views*, alternative to one another and to the ones we saw in the previous section. Exactly what kind of world-view they propose is what ultimately is at stake here, as we will see in the following section. For now let us quickly review the most promising solutions of the measurement problem, which are alternatives to Bohmian mechanics.

One possible response to the measurement problem can be seen as a way of making precise von Neumann's collapse postulate. In von Neumann's proposal the wave function collapses into one of the terms of the superpositions when a measurement is performed. As we saw this is problematical, since it is unclear what constitutes a measurement. Physicists GianCarlo Ghirardi, Alberto Rimini and Tulio Weber kept von Neumann's spirit that Schrodinger’s’ evolution gets interrupted by random collapses, but they made the idea precise rendering it a matter of natural law rather than the influence of a measurement [Ghirardi Rimini and Weber 1986]. In other words, the wave function evolves according to an equation which is essentially a “random” modification of Schrödinger's equation. This equation is such that the evolution is almost always the one of Schrödinger (and therefore creates superpositions), except at certain random times in which the wave function undergoes a spontaneous collapse into one of the terms of the superposition. This theory - called GRW theory, from the names of their proponents, or “spontaneous collapse theory” - is constructed in such a way that, in the case of macroscopic objects, the collapse happens almost immediately after the superposition formation. In this way, if macroscopic superpositions form, they disappear very quickly, explaining why they are never observed (for a review of the GRW theory, see [Ghirardi 2002]).

Finally, Hugh Everett developed the so called “many-worlds” theory. According to this theory the world is completely described by the wave function, evolving according to Schrödinger equation. As we know, this gives rise to macroscopic superpositions, but they are “taken care of” interpreting them as belonging to different worlds. In this way everything that can happen (all superposition terms), will happen, but in a different world [Everett 1957]. There are different takes on what constitutes in this theory a “world,“ but the point is that they are inaccessible to one another: so when a superposition forms, there is a formation of a different world for every different possible term of the superposition, and each of them can no longer interact with the others. In this way, contrarily to Bohmian mechanics and GRW theory, Everett's many worlds theory does not require any fundamental change of the mathematical formalism of ordinary quantum theory. It just requires a very complicated metaphysics of worlds (for a review of Everett's theory, see, among others, [Barrett 1998], [Vaidman 2002], [Wallace 2002]).

Note that all these theories, with the exception of GRW, are empirically equivalent to the early quantum theories: no experiment, in principle or in practice, can distinguish them. The GRW theory instead can give rise to different predictions, but it is currently well beyond our experimental capacities to detect these deviations.

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, and that do not presuppose the existence of two irreducible worlds. For this reason these theories have been called “quantum theories without observers” [Popper 1967]. What is interesting about them is that they do not require any fundamental change in the concepts to describe the quantum world. It will turn out though, that they still require a substantial change of the classical paradigm. To see why it is the case, let us analyze what pictures of the world these theories provide. As anticipated, all these theories were naturally taken to be theories *about the wave function*: the wave function mathematically represents a real, physical field that constitutes physical objects. For this reason we can talk about “wave function ontology” [Monton 2002]. Examples of this attitude can be found in [Albert 1996], [Lewis 2006], [Wallace 2003].

The strongest argument 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 think we are justified to take this object to represent matter. Consider for instance the mathematics of classical mechanics. The fundamental equation of this theory is Newton's equation: it a differential equation that describes the temporal evolution of a given mathematical object, a point in three-dimensional space. Since it is natural to interpret it as describing a point-like particle, we conclude that classical mechanics is a theory about the behavior of point-like particles, which constitute what exists in the world according to the theory. By analogy, when we do the same in the quantum framework, we obtain that the world is made of wave function. In fact, let us follow these steps for all the solutions of the measurement problem that we discussed:

1) identify the fundamental evolution equation;
2) identify what this equation defines the evolution of; and then
3) interpret this as representing what the world is made of.

In the many-worlds theory the fundamental equation is Schrödinger's equation, and it describes the temporal evolution of the wave function. So, for the same reasons we took the classical world to be made of particles, it seems natural to take the wave function to represent physical objects. Quite similarly in GRW theory the fundamental equation, even if it is some complicated alteration of Schrödinger's equation, determines the temporal evolution of the wave function. In Bohmian mechanics the situation is a little more complicated because there are two evolutions equations: one for point-like particles and another for the wave function. Be that as it may, the wave function is still part of the ontology. The conclusion is therefore that, no matter which quantum theory without observer one considers, the wave function is the natural candidate for the ontology of the quantum world.

A consequence of considering the wave function as the fundamental constituent of the world is that physical space, the space in which these constituents live, is very different from what we classically thought. That is, since in classical mechanics the microscopic constituents of the world are point-like particles that live in three-dimensional space and that evolve in time, physical space is three-dimensional space: the same in which the particles move. If instead the world is made of wave functions, physical space is the space on which the wave function is defined: this space is called "configuration space." Historically, configuration space has been introduced in classical mechanics for mathematical purposes. It is constructed from three-dimensional space: if there are N point-like particles, each with position r_i in three-dimensional space $\mathbb{R}^3$, then configuration space is defined as the space of the positions of all particles. That is, an element q of configuration space is given by $q=(r_1,r_2,\ldots,r_N)$. 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. So, 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.

If this reading of quantum theories is correct, then even if there are no irreducible worlds, there are no observers in the fundamental formalism of the theory, and we do not need to fundamentally change our concepts to describe the quantum world, we nonetheless have a substantial paradigm shift: we move from the classical, common-sensical view that there are microscopic objects in regular three-dimensional space (particles and/or fields) that compose macroscopic familiar objects, to the quantum view in which we all live together in configuration space, and we cannot use the classical rules of compositionality and reduction any longer. As a consequence, we need to develop new methods: if physical space is configuration space, this is where physical objects are. Clearly, this seems to be false: it seems obvious to us that we live in three-dimensions. Therefore, a proponent of the wave function ontology will have to provide an account of why it *seems as if* we live in three-dimensional space even though we do not. Similarly, one would need to explain how to "recover the appearances" of macroscopic objects in terms of the wave function. This is something that the proponents of such view are working on, and the current proposals are based on the addition of a number of supevenience rules. They are supposed to specify how to translate the language of the scientific image, given in terms of the wave function, into the macroscopic language of the manifest image, in which we talk, for instance, of particles being localized in space. Here is how the translation is supposed to go: we say that a particle of position x is in region R if and only if the proportion of the total square amplitude of x's wave function which is associated with points in R is greater than or equal to $1-p$ (where the parameter p is a conventional matter) [Albert and Loewer 1996].

Be that as it may, regardless of whether this approach is successful and satisfactory, the wave function ontology framework constitutes *the new quantum paradigm*. Even if the early quantum paradigms (Bohr, Wigner and von Neumann) were substituted by the new quantum paradigm we just saw, the shift from the classical paradigm is still substantial: the wave function lives on configuration space, and the classical explanatory scheme based on a microscopic ontology, classical compositionality and reductionism has to be drastically revised. In the next section we will see that there are other quantum paradigms which do not involve any radical change. They therefore provide a counterexample to the necessity thesis *NPS_cq* that the quantum world has to be described by a paradigm that involves a substantial change to the classical paradigm.

6. "Classical" Quantum Paradigms

Recently it has been recognized that *we do not have* to interpret quantum theories as theories of the wave function. And since the shift from the classical to the new quantum paradigm arises from taking the wave function as describing physical objects, if we do not do that then we can avoid a radical change in paradigm altogether. Various proposals have been made of quantum theories in which the wave function is not representing material objects but, as in classical theories, the world is described by trajectories of microscopic *stuff* in space-time that compose macroscopic objects. In this way we can develop a new but clear explanatory scheme, on the lines of the classical one, to account for the macroscopic world in terms of its microscopic constituents. If we take this route, there is no quantum revolution, or at least not the one advertised so far. In this section I describe how these proposals are supposed to work.

To understand where they come from, 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 both describe what there is. But arguably Bohmian mechanics is a theory *just* of particles, whose temporal evolution is governed by a Schrödinger evolving wave function. In other words, one can think of this theory so that the wave function does not describe matter: points in three-dimensional space do. Rather, the wave function helps to describe the way in which matter moves. In this way, we can think of the wave function as representing a law for the evolution of matter [Goldstein and Teufel 2001] or perhaps a property of matter [Monton 2002], and not matter itself. With this understanding of the role of the wave function in Bohmian mechanics, then one can look to the other quantum theories without observers and see whether we can think of the wave function in this way also in their context.

In GRW theory we have just the wave function, which evolves according to the Schrödinger evolution interrupted by random collapses. So it seems that this approach is not applicable: what can describe matter other than the wave function? Nonetheless, two distinct theories in which the wave function evolves according the same equation as the one in GRW (the modified Schrödinger evolution) have been proposed, and they are such that physical objects are not represented by the wave function. The first one was originally developed by Ghirardi and collaborators in [Benatti Ghirardi Grassi

1995], and the second one by Bell in [Bell 1987]. The first theory, dubbed "GRWm," is a theory in which, matter is described by a field in three-dimensional space, contrarily to the understanding of GRW presented in the previous section in which matter was described by the wave function. This field is defined in terms of the wave function, and represents the matter density of physical systems. The second theory, dubbed "GRWf," is a theory directly formulated in space-time: certain points in space-time are "full," and others are "empty," and the full ones are the ones in which matter is. These "full" points in space-time are called "flashes" because they are discontinuous, contrarily to what one is used to. In fact in classical mechanics matter is made of particles, which have continuous trajectories in space-time determined by Newton's equation: one can draw them without removing the pen from the paper. In contrast, in GRWf there are no continuous trajectories of matter. Rather we have just random "full" points that pop in and out of existence, and appear here now and there later. The reason why nobody notices is that everyone is made of flashes as well as everything else, and everyone goes in and out of existence along with the flashes. The rate of these flashes is determined by the wave function in terms of a well-defined equation. So, in both GRWm and GRWf the evolution of matter (the matter density field and the flashes, respectively) is determined by the wave function, which in turns evolves according to the modified GRW dynamics. In this way, we can think of the wave function in the same way as we did in Bohmian mechanics: not as representing matter but as a law or as a property of matter.

What about the many-worlds theory? [Allori *et al*. 2011] have argued that Schrödinger's original proposal that gave rise to the measurement problem was actually a many-worlds theory of this kind. In this theory, which they dubbed "Sm," matter is represented by a field in three-dimensional space that depends on the wave function, as in GRWm. In contrast to it, though, the wave function evolves according to Schrödinger's equation like in Bohmian mechanics. Contrarily to GRWm, where the matter field does not produce macroscopic superposition because the GRW evolution of the wave function quickly dumps all but one of the terms of the superposition, in Sm there are macroscopic superpositions, just like in many-worlds theories: in fact, since the wave function evolves according to Schrödinger's equation, it develops macroscopic superpositions, and these superpositions are inherited by the matter field. That is, Sm can be properly understood as a many-worlds theory, and the superpositions interpreted as belonging to different worlds. In this way, also in the case of many-worlds theories, matter is not necessarily described by the wave function, but by the matter field in three-dimensional space, and the wave function can be, again, taken as a law or as a property of matter. A non-exhaustive list of other possible quantum paradigms in which the wave function is not taken to represent physical objects can be found in [Allori *et al*. 2008]. To use another terminology the particles in Bohmian mechanics, the mass density in GRWm and Sm, and the flashes in GRW are the *primitive ontology* of the theory.

Notice that in this framework quantum theories have the same structure as classical theories: there is microscopic *stuff* in ordinary three-dimensional space that moves in time (except for GRWf in which the formulation is directly in space-time), and this microscopic *stuff* combines 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 using classical compositionality and reductionism, or some variants of it. There is no radical paradigm shift at all if one adopts one of these *"classical" quantum paradigms.*

Let me add some clarifications. First, one should not think that I am arguing that there are no important changes in going from a classical to a quantum description of the world: after all, quantum physics is not classical physics, so clearly there are some changes, and some are more important than others. Among the important ones there is nonlocality: as we saw, Bell's theorem has shown that the classical assumption of locality is false. But this does not mean that there was a paradigm shift, since this important change followed from a change in the laws of nature, and not in the world-view. In fact particles and fields in three-dimensional space are still around in these "classical" quantum paradigms, even if now they interact in ways that classically we thought were impossible.

Secondly, one could think that in the case of GRWf there is a fundamental change with respect to the classical paradigm: after all, these flashes are in space-time, they are discrete, discontinuous and random, and most of space-time is empty. It is unclear, though, whether or not this change is truly radical in the sense we are discussing here: while it is true that the world-view has changed, one could argue that these flashes are so small that we can proceed with our methodologies to determine macroscopic objects and properties *as if* there were no discrete flashes. Be that as it may, some work on deriving macroscopic properties from the quantum microscopic constituents has been accomplished, but more needs to be done, especially in the GRW framework. An antireductionist, again, would object to the whole project, but the point here is that within these quantum paradigms the reductionist is not worse off than within the classical framework. That is, whatever can be raised against reductionism in classical mechanics, in principle could also be raised here. But there seems to be no additional problem for reductionism due to just the fact that we are in the quantum framework.

Lastly, moving from classical to quantum mechanics, the dynamics governing matter changes. I do not regard this as a radical change in paradigm because this does not change any of its ingredients, even if perhaps a (strong) realist with respect to laws of nature would disagree.

7. Conclusion

To summarize and conclude:

1. When one refers to "quantum mechanics" she is not referring to a single theory. Rather, there are multiple ways to understand the quantum formalism, and they give rise to different quantum paradigms. Each of the quantum paradigms is substantially different from the classical one so that there is some sort of substantial paradigm shift going from classical to quantum physics.
2. The above needs a qualification: the radical paradigm shift necessary adopting the early quantum paradigms is different from the (less radical even if still substantial) paradigm shift using the new quantum paradigm;
3. Recently, new insights have shown that none of the above mentioned shift in paradigm is *necessary*: there are other "classical" quantum paradigms which do not involve a substantial paradigm shift. Therefore, whether or not there is a quantum revolution, embodied in a radical paradigm shift as *PS_cq* describe, is a matter of which quantum paradigm one decides to endorse: the early and the new quantum paradigm will make *PS_cq* true, but the "classical" paradigm will not. It is beyond the scope of this paper to assess which choice one should make. The point is that, contrarily to what is claimed, *NPS_cq* is false: it is possible to describe the quantum world within a paradigm that is not so radically different from the classical one, so that there is no necessity in having a quantum revolution.

References:

1. [Albert 1996] Albert, David Z.: Elementary Quantum Metaphysics. In: J. Cushing, A. Fine, and S. Goldstein (eds.), Bohmian Mechanics and Quantum Theory: An Appraisal. *Boston Studies in the Philosophy of Science* 184: 277-284 (1996).
2. [Albert and Loewer 1996] Albert, David. Z. and Barry Loewer: Tails of the

Schrödinger's Cat. In: R. Clifton (ed.), *Perspective on Quantum Realities.* Dordrecht, Reidel: 81–91 (1996).

3. [Allori *et al* 2008] Allori, Valia; Sheldon Goldstein, Roderich Tumulka and Nino Zanghi: On the Common Structure of Bohmian Mechanics and the Ghirardi-Rimini-Weber Theory. *British Journal for the Philosophy of Science* 59: 353{389 (2008).
4. [Allori *et al* 2011] Allori, Valia; Sheldon Goldstein, Roderich Tumulka and Nino Zanghi: Many-Worlds and Schrodinger's First Quantum Theory. *British Journal for the Philosophy of Science* 62 (1): 1-27 (2011)
5. [Aspect *et al.* 1981] Aspect, Alain; Philippe Grangier; Gerard Roger: Experimental Tests of Realistic Local Theories via Bell's Theorem. *Physics Review Letters **47***, 460 (1981).
6. [Bacciagaluppi and Valentini 2009] Bacciagaluppi,Guido; Anthony Valentini: *Quantum Theory at the Crossroads: Reconsidering the 1927 Solvay Conference.* Cambridge University Press (2009).
7. [Barrett 1998] Barrett, John: Everett's Relative-State formulation of Quantum Mechanics. *Encyclopedia of Philosophy*. Stanford University. June 3, 1998.

<http://plato.stanford.edu/entries/qm-everett/>

1. [Bell 1964] Bell, John Stuart: On the Einstein Podolsky Rosen Paradox. Physics 1, 3: 195-200 (1964). Reprinted as chapter 2 of *Speakable and Unspeakable in Quantum Mechanics*, Cambridge University Press (1987) and in Wheeler and Zurek (1983).
2. [Bell 1987] Bell, John Stuart: *Speakable and Unspeakable in Quantum Mechanics*. Cambridge University Press (1987).
3. [Benatti Ghirardi Grassi 1995] Ghirardi, GianCarlo; Fabio Benatti and Renata Grassi: Describing the Macroscopic World: Closing the Circle within bell the Dynamical Reduction Program. *Foundations of Physics* 25: 5-38 (1995).
4. [Bohm 1952] Bohm, David: A Suggested Interpretation of the Quantum Theory in Terms of Hidden" Variables, I and II. *Physical Review* 85: 166-193 (1952). Reprinted in Wheeler and Zurek (1983).
5. [Bohr 1949] Bohr, Niels: Discussions with Einstein on Epistemological Problems in Atomic Physics. In: P. A. Schlipp (ed.), *Albert Einstein: Philosopher-Scientist*. Library of Living Philosophers, Vol. VII, Evanston Illinois pp. 201-241 (1949).
6. [Cushing 1994] Cushing, James: *Quantum Mechanics: Historical Contingency and the Copenhagen Hegemony.* University Of Chicago Press (1994).
7. [de Broglie 1927] de Broglie, Louis: La nouvelle dynamique des quanta. In:

Rapports et Discussions du Cinquieme Conseil de Physique. Gauthier-Villars (1927). Reprinted in: G. Bacciagaluppi, A. Valentini (2009)

8. [Einstein Podolsky Rosen 1935] Einstein, Albert; Boris Podolsky, Nathan Rosen: Can Quantum-Mechanical Description of Physical Reality be Considered Complete? Physical Review 47 (10): 777-780 (1935). Reprinted in in Wheeler and Zurek (1983).
9. [Everett 1957] Everett, Hugh: Relative State Formulation of Quantum Mechanics. *Review of Modern Physics* 29: 454-462 (1957). Reprinted in Wheeler and Zurek (1983).
10. [Ghirardi, Rimini and Weber 1986] Ghirardi, GianCarlo; Alberto Rimini, Tulio Weber: Unified Dynamics for Microscopic and Macroscopic Systems. *Physical Review* D 34: 470-491 (1986).
11. [Ghirardi 2002] Ghirardi, GianCarlo: Collapse Theories. *Encyclopedia of Philosophy*. Stanford University. March 7, 2002.

<http://plato.stanford.edu/entries/qm-collapse/>

12. [Goldstein and Teufel 2001] Goldstein, Sheldon; Stefan Teufel: Quantum Spacetime without Observers: Ontological Clarity and the Conceptual Foundations of Quantum Gravity. In: C. Callender and N. Huggett (eds.) *Physics meets Philosophy at the Planck Scale*. Cambridge University Press (2001).
13. [Goldstein 2001] Goldstein, Sheldon: Bohmian Mechanics. *Encyclopedia of Philosophy*. Stanford University. October 26, 2001.

<http://plato.stanford.edu/entries/qm-bohm/>

14. [Greene 2005] Greene, Brian: *The Fabric of the Cosmos - Space, Time, and the Texture of Reality*. Vintage (2005).
15. [Heisenberg 1927] Werner Heisenberg: *Ueber den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik. Zeitschrift für Physik* 43 172-198. English translation in Wheeler and Zurek (1983).
16. [Heisenberg 1971] Heisenberg, Werner: *Physics and Beyond*. Harper and Row New York (1971).
17. [Kuhn 1962] Kuhn, Thomas: *The Structure of Scientific Revolutions*. The University of Chicago Press (1962).
18. [Landau and Lifshitz 1958] Landau, Lev, Evgeny Lifshitz: *Quantum Mechanics: Non-Relativistic Theory*. Vol. 3 . Pergamon Press (1958).
19. [Lewis 2006] Lewis, Peter: GRW: A Case Study in Quantum Ontology. *Philosophy Compass* 1: 224-244 (2006).
20. [Monton 2002] Monton, Bradley: Wave Function Ontology. *Synthese* 130: 265-277

(2002).
21. [Pauli 1927] Pauli, Wolfgang: comments in: *Rapports et Discussions du Cinquieme Conseil de Physique.* Gauthier-Villars (1927). Reprinted in: G. Bacciagaluppi, A. Valentini (2009).
22. [Popper 1967] Popper, Karl: Quantum Theory without "the Observer." In: M. Bunge (ed.), *Quantum Theory and Reality*, Springer (1967).
23. [Schrödinger 1935] Schrödinger, Erwin: Die gegenwärtige Situation in der Quantenmechanik, *Naturwissenschaften* 23: 807-812, 823-828, 844-849; English translation by Trimmer, J. D., 1980, The Present Situation in Quantum Mechanics: A Translation of Schrödinger's 'Cat Paradox' Paper, *Proceedings of the American Philosophical Society* 124: 323-338, reprinted in Wheeler and Zurek (1983).
24. [Sellars 1962] Sellars, Wilfrid: Philosophy and the Scientic Image of Man. In: R. Colodny (ed.), *Frontiers of Science and Philosophy*, Pittsburgh University Press (1962). Reprinted in: *Science, Perception and Reality*, Routledge (1963).
25. [Vaidman 2002] Vaidman, Lev: Many-Worlds Interpretation of Quantum Mechanics. *Encyclopedia of Philosophy*. Stanford University. March 24, 2002.
<http://plato.stanford.edu/entries/qm-manyworlds/>
26. [von Neumann 1932] von Neumann, John: *Mathematische Grundlagen der Quantenmechanik*, Springer (1932). English translation: *Mathematical Foundations of Quantum Mechanics*, Princeton University Press (1955).
27. [Wallace 2002] Wallace, David: Worlds in the Everett Interpretation. Studies in the History and Philosophy of Modern Physics 33: 637-661 (2002).
28. [Wallace 2003] Wallace, David: Everett and Structure. *Studies in the History and Philosophy of Modern Physics* 34: 87-105 (2003).
29. [Wheeler and Zurek 1983] Wheeler, John; Wojciech Zurek (eds) *Quantum Theory and Measurement.* Princeton University Press (1983).
30. [Wigner 1967] Wigner, Eugene: Remarks on the Mind Body Question. *American Journal of Physics* 35 (12): 1169–117 (1967).