Science and metaphysics: the case of quantum physics

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Abstract

The paper argues that doing metaphysics requires taking science into account and that doing so implies going as far as to take a stance as to what the appropriate formulation of the scientific theories in question is. I illustrate this claim by considering quantum physics. The famous measurement problem teaches us that answering the very question of what the appropriate formulation of quantum mechanics is requires employing the conceptual tools of philosophy. I first set out a general metaphysical framework that applies to all the different formulations of quantum mechanis (namely ontic structural realism), then consider the three different types of solution to the measurement problem and finally conclude that, despite appearances to the contrary, Bohm's claim to have provided the only ontologically serious formulation of quantum mechanics stands unrefuted.

1. Introduction

Metaphysics in the Aristotelian sense is not concerned with entities that are supposed to exist beyond the physical world, but with the fundamental traits of the physical world itself. That is why the treatise known to us as Aristotle's *Metaphysics* was ranged behind his *Physics*. Metaphysics in this sense cannot be done without taking science into account. Indeed, since its beginning in the Presocratics, metaphysics has been tied to science, and if people like Plato, Aristotle, Descartes, Hobbes, Leibniz, etc. set the paradigm for what philosophy is, it is evident that there is continuity between science and metaphysics. Separating metaphysics from science either leads to logically refined, but empty speculations about what are supposed to be possible worlds – a tendency in some quarters of today's analytic metaphysics that is with good reason criticized by Mulligan, Simons and Smith (2006) – or to abandoning philosophy and doing something else, such as history of ideas, or analysis of language.

How does one take science into account when doing metaphysics? A common instruction is to say that when doing metaphysics, one seeks to provide an answer to the question what the world is like under the assumption that our best scientific theories are – at least approximately – true. However, it is not evident why one needs philosophers to answer that question. Answering that question rather is what scientists are expected to do, what they are employed for by the general public via institutions such as universities, namely to find out the truth about the world. If the public, via the media, wants to know what the latest view of the world that, say, physics provides is, they of course invite physicists and not philosophers to answer that question. One may reply that the task of metaphysics is to develop a view of the world as a whole, whereas scientists have only their particular field of expertise in view. But it is not obvious why philosophers are needed to do that: a good TV moderator should be able to establish a dialogue between scientists from different fields so that in the end they come up with a coherent view of nature as a whole.

The problem with the instruction that one takes science into account when doing metaphysics by formulating an answer to the question what the world is like under the assumption that our best scientific theories are – at least approximately – true is that there is no straightforward answer to that question. If there were, we could indeed go back to the days of logical empiricism and envisage redefining philosophy as a sub-discipline of science, namely as the one that is concerned with the logical analysis of scientific theories, or simply follow James Ladyman when he proposes to let science speak for itself (e.g. Ladyman 2010). Ladyman is right in branding a widespread tendency in today's analytic metaphysics that sets out to take science into account, but fails to do so in limiting itself to mentioning oversimplified and outdated examples from classical physics instead of engaging with real science (Ladyman and Ross 2007, ch. 1). Nonetheless, he throws the baby of metaphysics out with the bathwater when he suggests that science speaks for itself.

There is no straightforward answer to the question what the world is like under the assumption that our best scientific theories are – at least approximately – true, for in setting out to answer that question, one has to take a stance as to what the appropriate formulation of the scientific theory in question is. One cannot simply read the theory in question off from textbooks, from experimental data, or from anything with which scientists deal in their daily business. One has to settle what the appropriate formulation of the scientific theory in question is by employing the conceptual, philosophical tools of argumentation in elaborating on the options in a clear and precise manner and laying out their consequences. That is why science needs philosophy – and, more generally speaking, our society needs philosophy when it wants science as an enterprise that seeks to find out the truth about the world. But that also means that doing metaphysics in the Aristotelian sense requires engaging with science itself, as it was in the days of Aristotle, Descartes, or Leibniz. It furthermore means that philosophy is not limited to professional philosophers. There is for instance no reason not to count Albert Einstein, or John Bell among the important philosophers of the 20th century, since their contributions to the foundations of space-time physics and quantum physics clearly live up to the standards of conceptual precision and clarity that David Lewis has established for analytic metaphysics. In short, there is continuity between science and metaphysics, since metaphysics is already needed when it comes to the appropriate formulation of the scientific theories themselves.

In the following, I shall consider the most obvious case to establish this claim, namely quantum mechanics. But similar considerations, albeit to a considerably less radical extent, apply to all the other major physical theories as well and also to many of the special sciences. To keep the paper brief and to the point, I have to grossly simplify; but all the points I'll make in the following can be backed up by extensive argument in the existing literature.

2. *The quantum measurement problem*

The formulation of quantum mechanics poses a problem that is known as the measurement problem. Consider the following conceptualization of this problem by Tim Maudlin (1995, p. 7):

"1.A The wave-function of a system is *complete*, i.e. the wave-function specifies (directly or indirectly) all of the physical properties of a system.

1. B The wave-function always evolves in accord with a linear dynamical equation (e.g. the Schrödinger equation).

1. C Measurements of, e.g., the spin of an electron always (or at least usually) have determinate outcomes, i.e., at the end of the measurement the measuring device is either in a state which indicates spin up (and not down) or spin down (and not up)."

The problem is that there can be no formulation of quantum mechanics that respects all three of these claims, because their conjunction is inconsistent: if the wave function yields a complete description of the dynamical properties of a physical system and if it always evolves according to a linear dynamical equation, then it is logically impossible that it evolves such as to represent a quantum system as having a determinate value of a dynamical property, such as a definite position or a definite value of spin, and a measuring device as indicating such a determinate value. We therefore have to give up one of these claims. Justifying which one of these claims is to go requires employing the conceptual tools of philosophy.

Note that the notion of measurement is immaterial to the formulation of this problem. There is no physical definition of what a measurement is, and it is impossible to give one: measurement interactions are not a special type of interactions in addition to the strong, the weak, the electromagnetic and the gravitational interactions, but are simply ordinary physical interactions; and measuring devices are not natural kinds in addition to electrons, protons, the chemical kinds, biological species, etc. Any macroscopic system capable of amplifying the properties of quantum systems can, on a given occasion, be used as a measuring device. One can therefore replace claim 1C above with the following, more general, but slightly more complicated claim:

1. C* The macroscopic systems with which we are familiar – such as, e.g. tables, chairs, cats, people and the like – always (or at least usually) have definite positions in space, and these systems are composed of microscopic quantum systems.

Consequently, quantum systems must at least sometimes have positions that are definite enough so that they can compose macroscopic systems that have definite positions. But if the wave-function specifies all the properties of quantum systems and if the wave-function always evolves in accord with a linear dynamical equation, it is logically impossible that quantum systems have positions that are definite enough so that they can compose macroscopic systems that have definite positions.

Let us briefly consider why quantum mechanics runs into this problem. The reason is the superposition principle. If, for instance, spin up and spin down are the two possible determinate values of the spin of an electron in any of the three orthogonal spatial directions, then quantum mechanics, by contrast to classical mechanics, allows not only states in which the electron has either spin up or spin down in a given direction, but also states in which both these values are superposed. In fact, such states are inevitable in quantum mechanics. If, for example, the electron is in a state in which it either has spin up or spin down in the x-direction, then this is a state in which it cannot have a determinate value of spin in the y-direction and in the z-direction; with respect to the y-direction and the z-direction, its state is a superposition of the values spin down and spin up. Suppose now that one sets up a device to measure the spin of the electron in the z-direction. Then if the dynamics of the quantum system always evolves according to a linear equation such as the Schrödinger equation, there is no possibility that the system will ever go into a state in which it has a determinate value of spin in the z-direction indicated by a measuring apparatus. But it is of course possible to make such measurements, and they have outcomes; the apparatus indicates either the value spin up or the value spin down at the end of such a measurement. A similar remark applies to all the other dynamical properties of quantum systems, notably their position in space.

When one considers two (or more) quantum systems that interact with each other, the situation becomes even more intriguing. The states of the two systems rapidly become entangled so that neither system has a determinate value of any of its dynamical properties. But there are certain correlations between the possible determinate values of the dynamical properties of the two systems, and these correlations remain whatever the spatial distance between the two systems may be in the future. Consider two electrons that are emitted together from a source in what is known as the singlet state and then become separated in space. Neither of them has a determinate value of spin in any direction, but there are correlations between them such that if one system acquires the value spin up in a given direction, the other system acquires the value spin down in that direction (and *vice versa*), whatever the spatial distance between the two systems may be. These correlations are well confirmed by experiments in which the two measurements are separated by a space-like interval. Consequently, these measurements cannot be connected by a signal that propagates at most with the velocity of light. The first of these experiments were carried out by Alain Aspect and his collaborators in Paris at the beginning of the 1980s (Aspect et al. 1982) and subsequently improved notably by the experiments performed by the group of Nicolas Gisin in Geneva (e.g. Tittel et al. 1998).

The theorem of John Bell from 1964 (reprinted in Bell 1987, ch. 2) proves that it is not possible to account for the correlations that quantum mechanics predicts and that are well-confirmed by these experiments on the assumption that these correlations are due to a common cause, such as the preparation of the pair of electrons in the singlet state at the source of the experiment. That is the famous *non-locality* of quantum mechanics: the probabilities for certain measurement outcomes to be obtained at a certain space-time point are not completely determined by what there is in the past light-cone of that point; quite to the contrary, events that occur at points separated by a space-like interval from that point contribute to determining the probabilities for what happens at that point. Thus, the outcome of a spin-measurement on the one electron changes the probabilities for the outcome of a spin-measurement on the other electron, although both electrons are separated by a space-like interval (see Maudlin 2011 for a detailed analysis of this non-locality).

3. A general ontological framework for any solution

A first step in a philosophical analysis of this situation is to enquire whether there are conditions that any account of quantum non-locality – and thus any solution to the measurement problem – has to respect in order to have a chance to succeed. At first glance, it may seem that admitting an interaction that propagates instantaneously over arbitrary distances in space is a general condition that any account of quantum non-locality is committed to – so that quantum non-locality compels us to reintroduce the commitment to action at a distance that Newton's theory of gravitation implied and that Einstein's theory of general relativity subsequently banned from physics. Einstein's vision of a physics free of action at a distance would thus have been rather short-lived. But this is not so. No attempt of an explanation of these correlations in terms of action at a distance has been pursued seriously in the literature (this option is mentioned in Chang and Cartwright 1993, part III, without being worked out or endorsed). In an experiment such as the one mentioned above on two electrons in the singlet state, there is a precise non-local correlation that obtains *only* between two space-like separated events, such as two space-like separated measurement outcomes. It is not clear how the hypothesis of a signal that propagates instantaneously throughout the *whole* of space could account for such a precise correlation limited to two specific events.

Reintroducing Newtonian action at a distance in order to account for the correlations between the space-like separated outcomes in a Bell experiment is attractive at first glance, since it seems obvious that, given their separation in space, the two quantum systems are separate entities in the sense that they have a state each independently of one another. To put it differently, if they were separate entities in this sense, such action at a distance would be the only way to account for the correlations (to be precise, one could also stipulate a signal that travels backwards in time, changing *after* the measurement the initial state at the source of the experiment – see Price 1996, ch. 8 and 9 –, but similar, if not even more severe objections apply to this proposal). Consequently, if one considers action at a distance to be a dead end, this means that the presupposition of separate states of the two quantum systems has to go. We thus get to acknowledging a certain form of *non-separability* and hence a certain sort of *holism* (Teller 1986): although the two quantum systems can be separated by an arbitrary distance in space, they remain connected by certain correlations that do not supervene on properties that belong to each of the two systems independently of the other one (that is, intrinsic properties). Consequently, it is not possible to attribute to each of these systems taken individually a state that completely specifies its properties.

This non-separablity is what is new in quantum theory. It contradicts Einstein's central idea implemented in the special – and also in the general – theory of relativity according to which all the factors that are relevant to what there is at a given point in space-time are situated in the past light-cone of that point (see Einstein 1948 for a clear statement). However, in contrast to what Einstein thought, this contradiction does not mean that we are forced to make a step backwards in readmitting Newtonian action at a distance. In recognizing non-separability, one makes a step forward to introducing a certain sort of holism in the philosophy of nature, leaving behind the philosophical atomism based on classical mechanics and classical field theories.

The position known as *ontic structural realism* in today's literatur (Ladyman 1998, French and Ladyman 2003, Ladyman and Ross 2007) can be considered as providing an ontological framework that seeks to make this holism precise. A structure can in this context be regarded as a network of concrete physical relations (such as the mentioned quantum correlations) that do not require underlying objects which possess an intrinsic identity, that is, an identity which is independent of these relations. There is no need to waive the commitment to objects in this context, as the position known as moderate ontic structural realism makes clear (Esfeld 2004, Esfeld and Lam 2008 and 2011): of course, if there are relations, there are objects as that what stands in the relations; but these relations – instead of intrinsic properties that provide for an intrinsic identity – are the ways (modes) in which the objects are. Thus conceived, ontic structural realism is an ontological framework suitable to accommodate quantum physics, whatever interpretation – and hence whatever solution to the measurement problem in dropping one of the three above mentioned claims – one endorses. Moreover, ontic structural realism reaches beyond quantum physics, being able to accommodate contemporary space-time physics as well (Esfeld and Lam 2008).

Already if one remains on this general level, ontic structural realism has important implications for the metaphysics of objects and properties, putting relations before intrinsic properties and rejecting the idea of an intrinsic identity of objects. It requires, for instance, to recognize, *pace* Mulligan (1998), what Mulligan calls "thick relations" in one's ontology. Furthermore, ontic structural realism implies a commitment to objective modality, thereby being incompatible with Humean metaphysics: the structures to which ontic structural realism is committed cannot be categorical and thus purely qualitative properties. They necessarily play a certain nomological role. To see this point, suppose that the physical concepts of mass and charge refer to intrinsic properties that are Humean categorical properties. There then is a possible world in which the property that plays the charge role in the actual world plays the mass role, and the property that plays the mass role in the actual world plays the charge role in that other world (that is why Humean metaphysics is committed to what is known as quidditism, see e.g. Lewis 2009). By contrast, it makes no sense to set out to conceive a possible world in which the structure that plays the role of the quantum relations of entanglement in the actual world plays the role of the spatio-temporal, metrical relations in another possible world (and *vice versa*). If something is a structure, it plays a certain nomological role necessarily, for certain relations are essential to it (Lyre 2010 and 2011 verbally disputes this claim in setting out a version of structural realism that is supposed to be Humean, but in fact confirms it in regarding certain symmetry relations as being essential for a structure).

One can go one step further in conceiving ontic structural realism as a general ontological framework for any interpretation of quantum physics that provides a solution to the measurement problem. Thus far, even if they necessarily play a certain nomological role, structures are not linked with a dynamics. If one sets out to develop ontic structural realism into one or another specific solution to the measurement problem, one has to integrate the structures of quantum entanglement into a certain dynamics so that the result is a solution to the measurement problem. One can provide a general criterion that any serious attempt to do so has to fulfil, although this claim is in dispute (see Psillos 2011 against Esfeld 2009): the nomological role that physical structures necessarily play is a causal role. In order to distinguish themselves as physical from mere mathematical structures and in order to be pertinent to the dynamics of physical systems, the structures have to be conceived as being causally efficacious. In other words, in virtue of building up certain structures, objects or events are causally efficacious so that it is the structures as a whole that bring about certain effects.

In sum, an important task of metaphysics is to provide a general, but nonetheless precise ontological framework on the basis of science that has to be respected by any serious interpretation of the science in question. Ontic structural realism is such a framework for quantum physics (indeed, current fundamental physics in general), being committed to structures in the sense of networks of concrete physical relations rather than objects with an intrinsic identity, without, however, waiving the commitment to objects (moderate structural realism) and conceiving these structures as being causally efficacious (causal structures) (Esfeld and Sachse 2011, ch. 2).

This *Festschrift* would be a good occasion to pursue the discussion with Kevin Mulligan about the metaphysical implications of these propositions. However, my aim here is a methodological one, namely to convince the community of those who pursue serious metaphysics that doing so requires engaging with science itself, and such an engagement goes farther than seeking to formulate a general ontological framework that any concrete interpretation of a given scientific theory has to satisfy; for these concrete interpretations can nevertheless radically differ in their ontological commitments. Therefore, if one is to make progress in obtaining truth about the actual world, one has to enter the business of developing such a concrete interpretation, and that requires taking a stance on the formulation of the scientific theory itself based on employing the argumentative tools of philosophy. Let us thus come back now to the measurement problem and see how the sketched general ontological framework works when it comes to developing a concrete and precise solution to this problem. Given that the problem consists in the conjunction of three prima facie plausible propositions being inconsistent, we have to discuss three types of solutions.

4. *A physical solution?*

When one confronts physicists with the claim that any solution to the measurement problem requires philosophical argument, one is likely to get the reply that there is a purely physical solution to this problem available which goes by the name of decoherence. Decoherence is based on taking the environment of a quantum system into account. Although decoherence does not lead to less, but to more entanglement, the quantum system becoming entangled with all the systems in its environment, the claim then is that due to the enormous number of degrees of freedom of the environment, a local observer does not have access to the entanglement; consequently, the world appears to her as if there were dynamical properties with determinate values. However, there is no justification for such a claim (see e.g. Adler 2003): first of all, there is no justification for introducing the notion of a *local* observer, since as long as one considers only the wave-function and decoherence, there is nothing in the theory that admits postulating the idea of systems that have a determinate position in space. Even if one allowed such a stipulation, the state of any local observer would rapidly become entangled with the state of the quantum system and the environment – it would simply be part and parcel of the overall entangled state. Consequently, there would not be any dynamical properties of the observer that could have a determinate value; in particular, she would have neither a determinate position, nor any determinate value of consciousness properties such as a measuring device appearing to her as being in a state which it indicates spin up (and not down) or spin down (and not up). In short, the vanishing of the interference terms in the wave-function (or the density matrix) known as decoherence by no means warrants the claim of there being local observers in consciousness states of determinate numerical values appearing to them.

In today's literature, it is widely acknowledged that drawing on decoherence alone does not yield a solution to the measurement problem (see e.g. Schlosshauer 2007, ch. 8 and 9). One usually interprets the physical significance of the vanishing of the interference terms in the following manner: decoherence induces a splitting of the universe into many branches that do not interact with each other. This is the basic idea of what is known as the many worlds interpretation of quantum mechanics. Thus, there is one branch of the universe in which the electron has spin up, the measuring device indicates spin up and the observer is in a consciousness state in which the measuring device appears as indicating spin up, and there is another branch of the universe in which the same electron has spin down, the same measuring device indicates spin down and the same observer is in a consciousness state in which the measuring device appears as indicating spin down. Since there are many measurements for which there are infinitely many possible outcomes – position measurements are a case in point –, this view is committed to maintaining that decoherence induces a splitting of the universe into infinitely many branches.

Note how radical this idea is: whenever there is decoherence, the whole universe splits into infinitely many branches so that each system in the universe – including its mass, its charge, etc. – is infinitely many times copied. Furthermore, the splitting concerns space-time itself: if all the systems in space-time are infinitely many times copied by creating branches that do not interfere with each other, then space-time itself is also infinitely many times copied; for if there were, say, a measuring device indicating spin up and the same measuring device indicating spin down existing in the same unique space-time region, contradictory predicates would be true of one and the same space-time region – indeed, in this case, almost all conceivable contradictory physical predicates would apply to more or less any space-time region. Moreover, since the splitting affects instantaneously the whole of space-time, this position apparently has to presuppose a globally preferred foliation of space-time into three-dimensional space and one-dimensional time in order to be able to define the idea of an *instantaneous* copying of all the systems in the universe induced by decoherence. By way of consequence, there thus cannot be a many worlds interpretation of quantum physics that respects the principle of the equivalence of all referential systems of special (and general) relativity (Lorentz-invariance).

On this view, subsequent to the splitting, the universe is a physical structure consisting in objects being infinitely many times copied in non-interfering branches of the universe whose dynamical properties have determinate values that are correlated across these branches (e.g. the electron having spin up in one branch is correlated with the same electron having spin down in another branch). There is no intrinsic identity of objects in a branch, since the values of their properties in one branch depend on the values of their properties in the other branches and are thus relational instead of intrinsic properties.

What about the situation prior to the splitting? Since the splitting is a real physical process, it is reasonable to ask about its cause. The only available answer within the many worlds interpretation is to say that the entangled state of the universe prior to the splitting is a causal structure that includes the disposition or the power to bring about a splitting of the universe into infinitely many branches through decoherence. However, we are told nothing about what the entangled state prior to the splitting is like: Does it consist in objects being smeared out in space-time that upon decoherence get split up into all their possible determinate values of position in different branches of the universe? If that state is not in time (as maintained e.g. by Kiefer 2004, ch. 10, on the basis of the timeless Wheeler-DeWitt equation in quantum gravity), how does it create a four-dimensional space-time with objects being localized in such a space-time and how does it, in doing so, bring about infinitely many copies of that space-time?

When pointing out the radical consequences of the many worlds interpretation, one often gets the reply that this is what the physical theory of quantum mechanics tell us, the physical theory being understood as being exhausted by the claims 1A and 1B above (or something that is equivalent to these claims). However, this is simply not true: claims 1A and 1B above talk about wave-functions, and decoherence in the sense of the vanishing of interference terms concerns wave-functions as well, but wave-functions (as well as state vectors, density matrices, etc.) are mathematical objects that are defined on a mathematical space. As long as one talks *only* in terms of wave-functions and the like, one has not said anything about the physical world. Wave-functions and the like are mathematical means of representing the physical world. The central issue in the interpretation of quantum mechanics is to develop a reply to the question what in the physical world the wave-function represents or refers to (cf. Maudlin 2010).

The radical idea of the many worlds interpretation is a possible reply to that question; but it certainly is not one that is simply imposed on us by the fact that one employs wave-functions in order to formulate quantum mechanics. It requires extensive argument to justify the claims and to answer the queries sketched out above. To strengthen this point, recall that all the empirical success of quantum mechanics consists in employing the wave-function to calculate probabilities for measurement outcomes by using the Born rule. However, there is no obvious place for probabilities in the many worlds interpretation: they cannot be probabilities for measurement outcomes, since this interpretation rejects claim 1C above – measurements do not have outcomes. It is not evident either how there could be probabilities that guide the decisions of rational beings, since any possible future of any rational being will certainly happen – for any possible future of myself, there is at least one future copy of myself that will experience that future in a branch of the universe (see the papers in Saunders et al. 2010 for a discussion of the many worlds interpretation).

5. *Bohm's quantum mechanics*

If upon consideration of the consequences of the many worlds interpretation of quantum mechanics as a view of *physical* reality one rejects this interpretation, then one has to come to terms with Bell's dictum that "Either the wavefunction, as given by the Schrödinger equation is not everything, or it is not right" (Bell 1987, p. 201). Bearing in mind the fact that the wave-function is a mathematical object and that as such it does not tell us what exactly in the physical world it represents, one may be tempted to give up claim 1A and maintain that the wave-function "is not everything": it does not tell the whole story about what there is in the physical world. Since nearly five decades now, we have a precisely formulated theory at our disposal that elaborates on this idea, namely Bohm's quantum mechanics (Bohm 1952, Bohm and Hiley 1993). Bohm's theory starts from the trivial fact that macroscopic systems such as measuring devices cannot have a determinate position unless the microscopic systems that compose them also have a rather determinate position. It then adds the – controversial – claim that these microscopic systems cannot acquire a rather determinate position in space and time unless they always have one. In other words, Bohm's theory introduces a determinate value of position for *any* physical system as an additional variable that is not specified by the wave-function. This variable is hidden in the case of microphysical systems in the sense that it is not possible to find out the exact positions of microphysical systems without changing them. On this basis, the quantum probabilities have the same status as the probabilities in statistical mechanics, namely to yield all the knowledge that we can obtain given our ignorance of the exact initial conditions.

Bohm's theory has long been ostracized, but during the course of a serious evaluation of proposals for an ontology of quantum mechanics in the last two decades or so, it has come to be acknowledged as being an important contender for an ontology of quantum mechanics (compare e.g. Putnam 1965 with Putnam 2005 as evidence for this change of attitude). The reason is that it is difficult to see what could be a knock down objection to Bohm's quantum mechanics: although the central version of this theory is formulated in terms of particles, a Bohmian quantum field theory can in principle be developed (see e.g. Bell 1987, ch. 19, and Dürr et al. 2004 and 2005). Bohm's theory is non-local in that the way in which the position of a given particle develops in time, its trajectory, depends in the last resort on the position of all the other particle in the universe – in other words, its position is not locally, but globally determined. But there is no reason to spell out this dependence in terms of superluminal energy or signal transmission. Indeed, the quantum potential or pilot wave, which may suggest such superluminal transmission, can be cut off the ontology of Bohm's quantum theory without loss (see e.g. Goldstein 2006, sections 5 and 15, penultimate paragraph).

The general framework for an ontology of quantum mechanics sketched out above in terms of (causal) ontic structural realism proves illuminating in this context: it precisely spells out the holism of the physical world to which Bohm has always seen his theory being committed (see e.g. the title of Bohm and Hiley 1993). Although Bohmian particles distinguish themselves by their position (no two particles can have the same position at the same time), this is not an intrinsic identity, since the position of particles is a relational property: the position of a given particle at a time is relative to the position of all the other particles at the same time. In other words, the ontology of Bohm's quantum mechanics consists in a structure of objects whose positions are correlated with each other. That structure as a whole is causal in that the structure of the world at a given time includes as a whole the disposition or power to develop in a certain manner in time. That disposition or power is expressed by a law of motion (see Dürr et al. 1997, in particular pp. 33-37). That is why the development of the position of any given particle (its trajectory) depends on the manner in which in the last resort the position of all the other particles develops. Thus spelled out, it is evident that there is no need for a commitment to a pilot wave or quantum potential that somehow pushes particles around.

It is, however, also evident that a Bohmian quantum theory cannot be formulated in a Lorentz-invariant manner. It has to presuppose a global temporal order of all events in the universe. The reason is that if one could know the exact positions of the particles, one could from that local knowledge infer in Bohm's quantum theory an objective foliation of space-time (however, since one cannot know the exact positions of the particles, it is also in Bohmian mechanics excluded that one could exploit the non-locality of quantum physics for a transmission of information between space-like separated events). It is not clear how forceful an objection one can build on the failure of Lorentz-invariance of Bohm's theory. Recall that the idea of an instantaneous splitting of the universe to which the many worlds interpretation is committed if it is to provide an ontology of the physical world cannot be spelled out in a Lorentz-invariant manner either.

As mentioned above, Bell's theorem proves that quantum theory regards events that are space-like separated from a given point in space-time as contributing to determining what there is at that point. The question can therefore only be whether despite this fact of quantum non-locality, it is possible to set out a Lorentz-invariant interpretation of quantum mechanics. One may object to this assessment that there is a relativistic quantum theory, namely quantum field theory. But of course also in quantum field theory, the probabilities for measurement outcomes at a certain space-time point or region depend on what there is at points or regions that are separated by a space-like interval from that point. As regards the demand for a

Lorentz-invariant account of these correlations, quantum field theory is in no better position than non-relativistic quantum mechanics. In sum, the decisive question for the assessment of Bohm’s quantum theory is whether one can do better: is it possible to elaborate on a complete, precise and credible ontology of what quantum mechanics tells us about the physical world without introducing additional variables and without forgoing Lorentz invariance?

6. Turning textbook quantum mechanics into an interpretation of quantum mechanics

In university courses and in standard textbooks from von Neumann (1932) on, quantum mechanics is presented in the form of a combination of two radically different dynamics: when no measurement is made, one uses a linear dynamical equation such as the Schrödinger equation in order to calculate the temporal development of the wave-function of a quantum system. However, when a measurement is made, the wave-function is supposed to collapse so that it represents the system as having one determinate value of the measured property at the exclusion of all the other ones – such as the spin of an electron having the value spin up (and not spin down) (or *vice versa*), or, more general, the quantum system having a determinate position. But the textbooks remain silent on what this sudden change of the wave-function is supposed to represent – a real physical change occurring in the world, or merely a change in our knowledge. If one settles for the latter option, one is committed to rejecting 1A and accepting additional variables, Bohm’s theory being the only precise one in that sense, since one then presupposes that the quantum system had a determinate position already before the measurement and that all what the measurement does is to reveal that position (change in our knowledge); if one spells this consequence out precisely, it then turns out that there is no need to reject 1B as well. If, by contrast, one takes this ambiguity in textbook quantum mechanics to be a reason to reject the idea of a wave-function collapse altogether and holds on to the textbook presupposition that the wave-function is a complete description of the properties of quantum systems, then one is committed to rejecting 1C – one then simply does not have the means to allow for measurements having outcomes and has to settle for an ontology along the lines of the many worlds interpretation.

But let us take textbook quantum mechanics literally, thus rejecting principle 1B above: the wave-function completely describes the properties of physical systems, but under some circumstances – measurements being a case in point – quantum systems change in such a way that they acquire a determinate value of position, that change being represented by the collapse of the wave-function. Is it possible to make this idea precise so that one specifies when (under what circumstances) and how this change happens? Doing so requires amending the Schrödinger equation. The only precise physical proposal in that sense goes back to Ghirardi, Rimini and Weber (1986) (GRW) (Gisin 1984 is a forerunner). GRW add a stochastic term to the Schrödinger equation such that, in brief, a single microscopic quantum system has a very low objective probability (propensity) to undergo a spontaneous localization (say once in 10^8 years). However, when one considers a macroscopic system that is composed of a huge number of microscopic quantum systems (say 10^{23}), one of these microscopic systems will undergo a spontaneous localization in less than a split of a second (10^{-15} years) so that, due to the entanglement, the whole system will be localized. When one couples a quantum system to a macroscopic system, due to the quantum system thus becoming entangled with the macroscopic system, it will also undergo a spontaneous localization in less than a split of a second. GRW provides a precise dynamics for the transition from quantum systems in superposed and entangled states to these systems acquiring classical properties such as notably a determinate localization so that they can then compose the well-localized macroscopic systems with which we are familiar (and some of which are capable of amplifying the properties of microscopic systems, being suitable to be used as measurement devices).

However, thus far there is only an improved dynamics of the temporal evolution of the wave-function construed in a mathematical space. It remains to be spelled out what in the physical world that dynamics represents. Again, taking textbook quantum mechanics literally, we have to say that a quantum system such as an electron, when not having a determinate value of position, is smeared out in space. What the GRW dynamics then achieves in improving on the collapse postulate in the textbooks is to describe how this position distribution smeared out in real physical space develops such as to be concentrated around a point. This is indeed the reading of the physical significance of the GRW dynamics that Ghirardi himself developed in proposing a mass density ontology (Ghirardi et al. 1995): the mass of, say, an electron when it has not a determinate position is literally smeared out in physical space, creating thus a mass density field. On this view, thus, the world is a structure of objects with smeared out values of their dynamical properties that are correlated with each other. That structure includes the disposition to develop under certain circumstances into correlated determinate values (see Dorato and Esfeld 2010 for the dispositionalist reading of GRW).

The mass density ontology of GRW cannot be spelled out in a Lorentz invariant manner, since exact knowledge of the mass density distribution would enable one to infer an objective foliation of space-time. But this is a feature that it shares with Bohm's theory and the postulate of a physical process of the splitting of the universe into infinitely many branches ("many worlds"). The most serious problem of the mass density ontology in contrast to at least Bohm's theory is that the story of a smeared out mass density developing into a determinate position cannot be told in a precise and consistent manner: the smeared out mass density can simply not evolve in such a way that it concentrates around a point; it may evolve in such a way that most of it is concentrated around a point in real physical space, but there will always be something left of it that is not located around that point. Consider what this means for the measurement of the spin of an electron in which the results spin up and spin down are equiprobable: the GRW amendment of the Schrödinger dynamics achieves that at the end of the measurement, the spin of the electron will be concentrated around one of these values, say spin up, but the value spin down will also always be there, albeit only in a tiny concentration so to speak. Accordingly, the mass density making up the measuring device will mostly be in the shape of the measuring device indicating spin up, but there also is a tiny mass density in the shape of the measuring device indicating spin down. This is known as the problem of the tails of Schrödinger's cat: even if Schrödinger's cat is alive, on the proposition under consideration here there also is a tiny dead cat. This problem cannot be solved by simply talking in terms of vagueness if we take the wave-function and its development according to the GRW dynamics literally as the complete description of what happens with the spin of an electron or the life of the cat, since the tiny spin down part of the wave-function of the electron or the tiny dead part of the wave-function of the cat has the same structural properties as the large spin up part or the alive part. If the one is real, so is the other, however small the other one will become in time (see Wallace 2008, sections 2.5.2 to 2.5.4 for a presentation of the state of the art and e.g. Maudlin 2010, pp. 134-139, for an argumentation why this is a fatal objection to the GRW mass density theory). But this means that it is impossible to take textbook quantum mechanics literally: as things stand, there is no prospect of it turning out to be possible to elaborate on the idea of a dynamics that includes a development from smeared out values of physical properties to determinate values in a physically precise manner.

However, this is not the end of the project of building an ontology of quantum physics on GRW. There is another reading of the GRW dynamics possible that entirely drops the idea of there being smeared out values in the physical world. That reading is due to Bell (1987, p. 205). A good way to access it is via a comparison with Bohm's quantum theory: in Bohm's theory, quantum systems *always* have a determinate position, and the determinate value of position is not taken into account in the wave-function description. According to what is known as the GRW flash theory, quantum systems have a determinate value of position *only* when the wave-function as developing according to the GRW modification of the Schrödinger dynamics indicates such a value, that is, when a spontaneous localization occurs, and these sparse determinate positions are *all* there is in the world. To put it differently, the spontaneous localizations that GRW postulate are conceived as flashes centred around space-time points, and these flashes are all there is in space-time. Starting with an initial distribution of flashes, the wave-function is nothing more than a tool to calculate the probabilities for the occurrence of further flashes. On this view, the collapse of the wave-function is a misleading description of the fact that new flashes occur and that, consequently, the information available for the calculation of the probabilities for the further occurrences of future flashes has to be updated (see Allori et al. 2008 for an illuminating comparison of the ontologies of Bohm, GRW mass density and GRW flashes).

Nonetheless, the GRW flash theory is a realist interpretation of quantum mechanics that proposes a complete ontology: inherent to each flash is a propensity to produce a further flash – if we consider only one flash taken in isolation, that propensity is so weak that an isolated flash will produce another flash only every 10^8 years. That production thus occurs across a huge gap in space-time. However, in any scenario that is to apply to the real world, we have to start with a large initial distribution of flashes, and to that distribution as a whole inheres the propensity to produce large numbers of further flashes. In other words, we have a causal structure of correlated flashes that has the propensity or disposition to produce further correlated flashes. That structure is non-local in the sense that in calculating the probabilities for further flashes, one has to take flashes that are separated by space-like intervals into account. Ontologically speaking, this means that the propensity of a given distribution of flashes to produce further flashes extends over space-like separated intervals.

The flash ontology is such that its dynamics can be formulated in a Lorentz-invariant manner, since it abandons the idea of continuous trajectories of anything in space-time (such as Bohmian particles or field values, or mass densities in Ghirardi's ontology for GRW). Even if one had exact knowledge of the flash distribution, one could not infer from that knowledge an objective foliation of space-time (see Tumulka 2006 and Maudlin 2011, ch. 10). More precisely, as things stand, it is the *only* worked out proposal for an interpretation of quantum mechanics (or quantum field theory for that matter) that has the chance of being Lorentz-invariant (the chance, since the formulation of Tumulka 2006 does not take interacting fields into account). Furthermore, the GRW dynamics – both in the flash version and the mass density version – is the only formulation of quantum mechanics that includes an indeterministic dynamics and, moreover, a fundamental law of nature that is not time-reversal invariant.

The GRW ontology is sparse, but it does the job of accounting for macroscopic objects whose properties have determinate values (and some of which can be used as measuring devices): macroscopic objects are, as Bell put it, galaxies of flashes (Bell 1987, p. 205). Maudlin (2011, pp. 257-258) raises as the main objection against the flash ontology that it implies the radical falsity of our standard conception of macroscopic objects such as DNA strands. However, it seems that this objection can be countered: GRW flashes are events at space-time points. The unification of space and time in relativity physics is a very good argument for adopting an event ontology, known as four-dimensionalism, and for considering macroscopic objects as sequences of events that fulfil certain similarity criteria (Balashov 2010). What the flash ontology abandons is the idea of these sequences being continuous – there is empty space-time between the events on the flash ontology. But there are enough flashes to constitute sequences of events that make up macroscopic objects such as DNA strands.

However, there is another, much more serious problem for the flash ontology. Consider the question of what a measuring device interacts with when it is supposed to measure a quantum system such as an electron. On the flash ontology, there is nothing with which the measuring device interacts – there is no particle that enters it, and no wave or mass distribution that touches it either. There is only a flash in its past light-cone. That flash has the propensity to produce a further flash, and that propensity is supposed to be triggered by the measuring device, but that propensity is not a wave or a field that stretches out in space-time so that there is some physical entity or other with which the measuring device could interact. The quantum system that is to be measured is supposed to be coupled with the huge configuration of quantum systems that make up the measuring device, thereby to become entangled with that huge configuration, and that entanglement lasts only for a tiny split of a second, since there immediately occurs a GRW hit in that huge configuration. However, this story does not make sense on the flash ontology, since there is nothing with which the measuring device could interact or which could be coupled to it (unless one were to stipulate that it directly and retroactively interacts with the flash in its past light-cone).

The GRW flash theory has the great advantage of being the only known interpretation of quantum mechanics that is Lorentz-invariant. That result is achieved through an extreme ontological parsimony: there are only occasionally flashes at space-time points, the most of space-time being empty. Filling out space-time with more than these flashes – such as continuous trajectories of flashes making up particle positions or a mass density distribution that is more or less everywhere and at some points concentrated – would destroy the Lorentz invariance. But if there are only GRW-flashes, it seems that space-time is not filled out enough for there to be measuring interactions of quantum systems. In sum, there is a tool for calculating probabilities for further flashes, but it seems that the flash version of GRW hardly is a candidate for a serious ontology of quantum mechanics.

7. Conclusion

If one wants a metaphysics that gives us a fundamental ontology of what there is in the world, one has to take physics into account. Quantum mechanics is our currently best theory of what there is in the world. But it is not possible to employ the tools of metaphysics – such as logic and conceptual analysis – in order to simply read off an ontology from quantum theory. In setting out to do so, one has to engage with the science itself and settle for a formulation of quantum theory on the basis of employing the conceptual tools of philosophy. All the positions considered in this paper differ in the formalism of quantum physics that they propose, and they radically differ in their ontological commitments. A universe that splits into ever more infinities of non-interfering branches, particles (or field entities) with continuous trajectories in space-time, smeared out and overlapping mass densities, or flashes occurring occasionally at space-time points are radically different proposals for a fundamental ontology. Nonetheless, they all fall within the general ontological framework of (causal) ontic structural realism, and they are all empirically adequate in the sense that they all yield correct predictions for all known experiments.

One may consider this situation to be one of underdetermination. But this is so only at a superficial glance. The task of philosophy is first to formulate a general ontological framework that can accommodate quantum physics on whatever interpretation (such as (causal) ontic structural realism) and then to precisely spell out the different ontological options that go with the different formulations of quantum mechanics (different solutions to the measurement problem) and to lay out their consequences. Once this is done, the impression of underdetermination vanishes, and one can be happy if one is left with a single position that can stand firm.

This conclusion is of course controversial. Nonetheless, to end this paper, here is my assessment stated in a quick and dirty manner: the mathematical elegancy of working only with the wave-function formalism and the Schrödinger dynamics loses its appeal as soon as one spells out its consequences for an ontology of the *physical* world (by contrast to confining oneself to wave-functions in an abstract mathematical space), namely instantaneous splittings of the universe into ever more infinities of branches in which every physical system including space-time itself is duplicated infinitely many times. Since trying to understand quantum mechanics for the above mentioned reasons that doing metaphysics requires engaging with science, I've hoped that it is possible to turn textbook quantum mechanics into a credible interpretation by integrating the collapse postulate into an amended Schrödinger dynamics. But doing so on the basis of taking the idea of smeared out quantum systems literally whose state collapses into rather precise positions under certain conditions (the GRW mass density theory) does not work because all the structure of the system will always remain to a certain extent concentrated elsewhere in space as well (the tails problem). Bell's idea of a GRW flash ontology does not encounter this problem, but it seems that it is too sparse to yield a credible ontology, since there is nothing with which a measurement device could interact. My tentative conclusion therefore is that given the state of the art, Bohm's claim to have provided the *only* ontological interpretation of quantum theory (e.g. Bohm and Hiley 1993, preface and ch. 1.1) is not refuted.

References

Adler, Stephen L. (2003): “Why decoherence has not solved the measurement problem: a response to P. W. Anderson”. *Studies in History and Philosophy of Modern Physics* 34, pp. 135-142.

Allori, Valia, Goldstein, Sheldon, Tumulka, Roderich and Zanghì, Nino (2008): “On the common structure of Bohmian mechanics and the Ghirardi-Rimini-Weber theory”. *British Journal for the Philosophy of Science* 59, pp. 353-389.

Aspect, Alain, Dalibard, Jean and Roger, Gérard (1982): “Experimental test of Bell’s inequalities using time-varying analyzers”. *Physical Review Letters* 49, pp. 1804-1807.

Balashov, Yuri (2010): *Persistence and spacetime*. Oxford: Oxford University Press.

Bell, John S. (1987): *Speakable and unspeakable in quantum mechanics*. Cambridge: Cambridge University Press.

Bohm, David (1952): “A suggested interpretation of the quantum theory in terms of ‘hidden’ variables”. *Physical Review* 85, pp. 166-193.

Bohm, David and Hiley, Basil (1993): *The undivided universe. An ontological interpretation of quantum theory*. London: Routledge.

Chang, Hasok and Cartwright, Nancy (1993): “Causality and realism in the EPR experiment”. *Erkenntnis* 38, pp. 169-190.

Dorato, Mauro and Esfeld, Michael (2010): “GRW as an ontology of dispositions”. *Studies in History and Philosophy of Modern Physics* 41, pp. 41-49.

Dürr, Detlef, Goldstein, Sheldon, Tumulka, Roderich and Zanghì, Nino (2005): “Bell-type quantum field theories”. *Journal of Physics A* 38, pp. R1-R43.

Dürr, Detlef, Goldstein, Sheldon and Zanghì, Nino (1997): “Bohmian mechanics and the meaning of the wave function”. In: R. S. Cohen, M. Horne and J. Stachel (eds.): *Experimental metaphysics. Quantum mechanical studies for Abner Shimony. Volume 1*. Dordrecht: Kluwer. Pp. 25-38.

Dürr, Detlef, Goldstein, Sheldon and Zanghì, Nino (2004): “Bohmian mechanics and quantum field theory”. *Physical Review Letters* 93, pp. 090402:1-4.

Einstein, Albert (1948): “Quanten–Mechanik und Wirklichkeit”. *Dialectica* 2, pp. 320-324.

Esfeld, Michael (2004): “Quantum entanglement and a metaphysics of relations”. *Studies in History and Philosophy of Modern Physics* 35, pp. 601-617.

Esfeld, Michael (2009): “The modal nature of structures in ontic structural realism”. *International Studies in the Philosophy of Science* 23, pp. 179-194.

Esfeld, Michael and Lam, Vincent (2008): “Moderate structural realism about space-time”. *Synthese* 160, pp. 27-46.

Esfeld, Michael and Lam, Vincent (2011): “Ontic structural realism as a metaphysics of objects”. In: A. Bokulich and P. Bokulich (eds.): *Scientific structuralism*. Dordrecht: Springer. Pp. 143-159.

Esfeld, Michael and Sachse, Christian (2011): *Conservative reductionism*. New York: Routledge.

French, Steven and Ladyman, James (2003): “Remodelling structural realism: quantum physics and the metaphysics of structure”. *Synthese* 136, pp. 31-56.

Ghirardi, Gian Carlo, Grassi, Renata and Benatti, Fabio (1995): “Describing the macroscopic world: Closing the circle within the dynamical reduction program”. *Foundations of Physics* 25, pp. 5-38.

Ghirardi, Gian Carlo, Rimini, Alberto and Weber, Tullio (1986): “Unified dynamics for microscopic and macroscopic systems”. *Physical Review D* 34, pp. 470-491.

Gisin, Nicolas (1984): “Quantum measurements and stochastic processes”. *Physical Review Letters* 52, pp. 1657-1660 (and reply p. 1776).

Goldstein, Sheldon (2006): “Bohmian mechanics”. In: E. N. Zalta (ed.): *Stanford Encyclopedia of Philosophy*. http://plato.stanford.edu/entries/qm-bohm (consulted 17 May 2011)

Kiefer, Claus (2004): *Quantum gravity*. Oxford: Oxford University Press.

Ladyman, James (1998): “What is structural realism?” *Studies in History and Philosophy of Modern Science* 29, pp. 409-424.

Ladyman, James (2010): “Reply to Hawthorne: physics before metaphysics”. In: S. Saunders, J. Barrett, A. Kent and D. Wallace (eds.): *Many worlds? Everett, quantum theory, and reality*. Oxford: Oxford University Press. Pp. 154-160.

Ladyman, James and Ross, Don with Spurrett, David and Collier, John (2007): *Every thing must go. Metaphysics naturalised*. Oxford: Oxford University Press.

Lewis, David (2009): “Ramseyan humility”. In: D. Braddon-Mitchell and R. Nola (eds.): *Conceptual analysis and philosophical naturalism*. Cambridge (Massachusetts): MIT Press. Pp. 203-222.

Lyre, Holger (2010): “Humean perspectives on structural realism”. In: F. Stadler (ed.): *The present situation in the philosophy of science*. Dordrecht: Springer. Pp. 381-397.

Lyre, Holger (2011): “Structural invariants, structural kinds, structural laws”. In: D. Dieks, W. Gonzalez, S. Hartmann, M. Stöltzner and M. Weber (eds.): *Probabilities, laws, and structures*. Dordrecht: Springer.

Maudlin, Tim (1995): “Three measurement problems”. *Topoi* 14, pp. 7-15.

Maudlin, Tim (2010): “Can the world be only wavefunction?” In: S. Saunders, J. Barrett, A. Kent and D. Wallace (eds.): *Many worlds? Everett, quantum theory, and reality*. Oxford: Oxford University Press. Pp. 121-143.

Maudlin, Tim (2011): *Quantum non-locality and relativity. Third edition*. Chichester: Wiley-Blackwell.

Mulligan, Kevin (1998): “Relations – through thick and thin”. *Erkenntnis* 48, pp. 325-353.

Mulligan, Kevin, Simons, Peter and Smith, Barry (2006): “What’s wrong with contemporary philosophy?” *Topoi* 25, pp. 63-67.

Price, Huw (1996): *Time’s arrow and Archimedes’ point. New directions for the physics of time*. Oxford: Oxford University Press.

Psillos, Stathis (2011): “Adding modality to ontic structuralism: an exploration and critique”. In: E. Landry and D. Rickles (eds.): *Structure, object, and causality*. Dordrecht: Springer.

Putnam, Hilary (1965): “A philosopher looks at quantum mechanics”. In: H. Putnam (ed.): *Mathematics, matter and method. Philosophical papers. Volume 1*. Cambridge: Cambridge University Press. Pp. 130-158.

Putnam, Hilary (2005): “A philosopher looks at quantum mechanics (again)”. *British Journal for the Philosophy of Science* 56, pp. 615-634.

Saunders, Simon, Barrett, Jonathan, Kent, Adrian and Wallace, David (eds.) (2010): *Many worlds? Everett, quantum theory, and reality*. Oxford: Oxford University Press.

Schlosshauer, Maximilian (2007): *Decoherence and the quantum-to-classical transition*. Berlin: Springer.

Teller, Paul (1986): “Relational holism and quantum mechanics”. *British Journal for the Philosophy of Science* 37, pp. 71-81.

Tittel, W., Brendel, J., Gisin, B., Herzog, T., Zbinden, H. and Gisin, N. (1998): “Experimental demonstration of quantum-correlations over more than 10 kilometers”. *Physical Review* A57, pp. 3229-3232.

Tumulka, Roderich (2006): “A relativistic version of the Ghirardi-Rimini-Weber model”. *Journal of Statistical Physics* 125, pp. 821-840.

von Neumann, Johann (1932): *Mathematische Grundlagen der Quantenmechanik*. Berlin: Springer. English translation *Mathematical foundations of quantum mechanics. Translated by R. T. Beyer*. Princeton: Princeton University Press 1955.

Wallace, David (2008): “Philosophy of quantum mechanics”. In: D. Rickles (ed.): *The Ashgate companion to contemporary philosophy of physics*. Aldershot: Ashgate. Pp. 16-98.